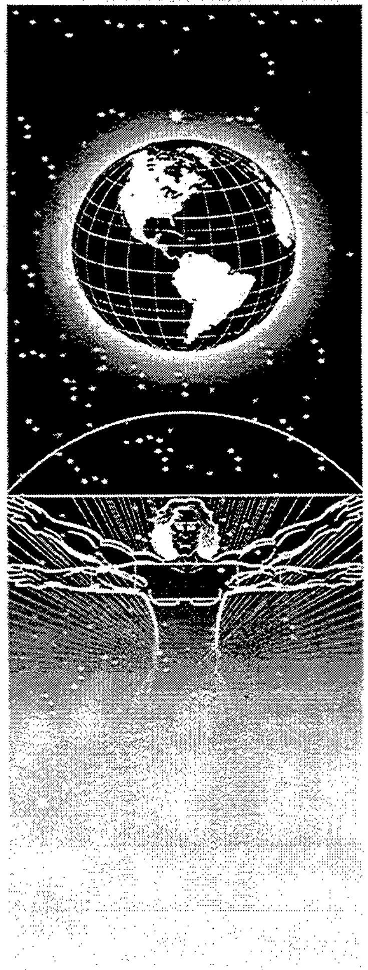
AFRL-HE-WP-TR-1998-0026



UNITED STATES AIR FORCE RESEARCH LABORATORY

EVALUATION OF AIR EMISSIONS-REDUCTION TECHNOLOGIES FOR AEROSPACE GROUND EQUIPMENT

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April 1998

Final Report for the Period July 1995 to December 1996

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AFRL-HE-WP-TR-1998-0026

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1998	Final Report 25 Jul 95 - 31 Dec 96

4. TITLE AND SUBTITLE
Evaluation Air Emissions-Reduction Technologies for Aerospace Ground Equipment

5. FUNDING NUMBERS
Contract No. F33657-92-D-2055

PE 63106F
PR 2745
TA 00
W 22

6. AUTHOR(S)
James J. Reuther

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Human Effectiveness Directorate
Deployment and Sustainment Division
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7901

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-HE-WP-TR-1998-0026

11. SUPPLEMENTARY NOTES
Task was performed under a Scientific Services Program Agreement issued by Battelle, Supportability Investment Decision Analysis Center (SIDAC)

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Reported are results of a US Air Force effort to reduce air emissions from aerospace ground equipment (AGE), called the "Green Age" initiative. In Phase I, promising NO_x -reduction technologies were identified for deployment on A/M32A-86("-86") generators at March AFB, California. In Phase II, Battelle was contracted to devise and use a numerical rating system by which to evaluate these technologies for merit. The Rating system had five criteria, totally 100 points: Emission Reduction (25), Cost (25), Reliability/Maintainability (20), Deployability (20), and Fidelity of Data (10). A reduction in NO_x of $\geq 70\%$ was the prime requirement, with no accompanying increase in the emission of carbon monoxide, particulates, or reactive hydrocarbons. Based on this numerical Rating system, the six candidate Green Age NO_x -reduction technologies considered were ranked in the following order of decreasing merit: 1) Water-in-Fuel Firing (WFF), WL/FIVC, Tyndall AFB FL; 2) Selective Catalytic Reduction (SCR), Houston Industrial Silencing (HIS) TX; 3) NO_x-Filter Cart (NFC), AL/EQ, Tyndall AFB FL; 4) Dual-Fuel Firing (DFF), BKM, San Diego CA; 5) Oxygen-Enriched Air (OEA), AL/FTS, Brooks AFB TX; and 6) Non-Thermal Discharge (NTD), WL/MNMW, Eglin AFB FL. WFF< SCR, and NFC are recommended for further development and demonstration under Green AGE Phase III. DFF, OEA, and NTD have technical deficiencies, the resolution of which is doubtful, technically or within time.

14. SUBJECT TERMS
Aerospace ground equipment, NO_x, CO reduction, dual-fuel-firing, non-thermal discharge, oxygen-enriched air, selective-catalytic reduction, water-in-fuel firing, NO_x filtering, US Air Force, Green Age Initiative

15. NUMBER OF PAGES
83

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	SAR	SAR	SAR

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EVALUATION OF AIR EMISSIONS-REDUCTION TECHNOLOGIES FOR AEROSPACE GROUND EQUIPMENT

SUMMARY

Reauthorization of the Clean Air Act *may* levy air-quality standards on the United States Air Force (USAF). After learning that Aerospace Ground Equipment (AGE) at March AFB, CA, did not meet the standards for nitrogen-oxides (NOx) emissions set forth by the South Coast Air Quality Management District, the USAF established a team to identify, develop, and demonstrate hardware solutions to this air-emissions problem. The project is referred to as the "Green AGE Initiative".

To ensure that USAF systems are capable of meeting peacetime requirements, the Logistics Research Division of the Operational Logistics Branch of Armstrong Laboratory solicited military and civilian laboratories to identify current technologies that could bring March AFB into compliance.

In Phase I, technologies were identified as having promise with regard to solving the March AFB problem. In Phase II, these candidate emissions-control technologies were to be demonstrated by their proponents on actual Green AGE equipment, and then evaluated for technical merit. Promising technologies would then be developed and demonstrated further in Phase III of Green AGE.

Battelle was contracted by the USAF to perform the Phase II evaluation of merit. Tasks included designing and using a Rating System to identify the one, or more, emissions-reduction technologies meriting further development in Green AGE Phase III. The candidate AGE in this proof-of-concept demonstration was an "A/M32A-86", or "dash 86" ("-86") generator.

The Rating System had 5 criteria, totaling 100 points: Emissions Reduction (25), Cost (25), Reliability/Maintainability (20), Deployability (20), and Fidelity of Data (10).

A reduction in NOx emissions of ≥70% was the prime requirement, with no accompanying increase in the emission of carbon monoxide, particulates, or reactive hydrocarbons.

Based on this numerical Rating System, the 6 candidate Green AGE NOx-reduction technologies considered were ranked in the following order of decreasing merit:

1. **Water-in-Fuel Firing (WFF), WL/FIVC, Tyndall AFB, FL;**
2. **Selective-Catalytic Reduction (SCR), Houston Industrial Silencing, TX;**
3. **NOx-Filter Cart (NFC), AL/EQ, Tyndall AFB, CA;**
4. **Oxygen-Enriched Air (OEA), AL/CFTS, Brooks AFB, TX;**
5. **Dual-Fuel Firing (DFF), BKM, San Diego, CA; and**
6. **Non-Thermal Discharge (NTD), WL/MNMW, Eglin AFB, FL.**

The top-3 technologies, WFF, SCR, and NFC, are recommended for further development and demonstration under Phase III. Of these 3 technologies, WFF and SCR are somewhat more promising than NFC. Each technology has some technical problems, most of which appear solvable.

The last 3 technologies, DFF, OEA, and NTD, have technical deficiencies, the resolution of which is doubtful within the time a Green AGE technology may be needed at March AFB (NTD), or doubtful technically, because they (DFF and OEA) cannot meet the minimum NOx-reduction requirement.

ACKNOWLEDGMENTS

This task was supervised by Jill Ritter (né Easterly), Armstrong Laboratory, Wright-Patterson AFB, and sponsored by the Supportability Investment Decision Analysis Center (SIDAC).

The cooperation of the following Green AGE technology-proponents was greatly appreciated:

BKM, San Diego, CA: John Kelly and Steve Nussbaum

WL/MNMW, Eglin AFB, FL: Steve Federle

AL/CFTS, Brooks AFB, TX: Capt. Jerold Fenner and John Ohlhausen

Houston Industrial Silencing, Houston, TX: Harold Harris

WL/FIVC, Tyndall AFB, FL: Aly Shaaban and Paul Sheppard

AL/EQ, Tyndall AFB, FL: Alan Canfield

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for
EVALUATION OF AIR EMISSIONS-REDUCTION TECHNOLOGIES FOR AEROSPACE GROUND EQUIPMENT
to
OC AL HSC/HRG
Wright-Patterson AFB, OH

December 20, 1996

1.0 INTRODUCTION

Reauthorization of the Clean Air Act by the Environmental Protection Agency (EPA) *may* levy air-quality standards on the United States Air Force (USAF) [1-4]. After finding that flight-line Aerospace Ground Equipment (AGE) at March AFB, CA, did not meet nitrogen-oxides (NOx) emissions standards set forth by the South Coast Air Quality Management District (SCAQMD), the USAF established a team to identify, develop, demonstrate, and implement hardware solutions to this potential air-emissions problem [2-4]. The project is referred to as the "Green AGE Initiative".

To ensure that USAF systems are capable of meeting peace-time requirements, the Logistics Research Division of the Operational Logistics Branch of Armstrong Laboratory solicited military and civilian laboratories to identify current technologies that could bring March AFB into compliance.

In Phase I, candidate technologies were identified as having promise with regard to solving the March AFB problem [2,3]. In Phase II, these emissions-control technologies were to be demonstrated by their proponents on actual Green AGE equipment, and then evaluated for technical merit. Promising technologies would then be further demonstrated in Phase III of Green AGE.

2.0 OBJECTIVE

Battelle was contracted by the USAF to perform the Phase II evaluation. First tasks included designing a Test Plan for the demonstrations and formulating a Rating System for the evaluation. The basis for the Test Plan and Rating System is given in Appendix 1. Elements of the Rating System were based on the exit criteria of Green AGE Phase I [2,3].

The final Battelle Phase-II task was to use the Rating System to identify the one, or more, emissions-reduction technologies meriting further development in Green AGE Phase III.

The results of this final task are the focus of this report. Information for this analysis was gathered from on-site briefings, as well as from available reports and the technical literature [1-24].

3.0 CANDIDATE AGE AND EMISSIONS-REDUCTION TECHNOLOGIES

The following sections describe the AGE and technologies evaluated in Green AGE Phase II.

3.1 Aerospace Ground Equipment (AGE)

The AGE in the proof-of-concept demonstration was an "A/M32A-86", or "dash 86" ("-86") generator, rated at 72 kilowatts (kW), 200 amps, 115 volts/3-phase. There are reportedly 53 such units at March AFB [2]. The generator's engine is a Detroit Diesel (no endorsement implied), a supercharged, 2-stroke, 4-cylinder, 2000-rpm, compression-ignition device, rated at 148 brake horsepower [2,4]. Actual -86s were provided by the USAF to each site for the express purpose of demonstrating candidate Green AGE NOx-reduction technologies. These -86s were fired on diesel fuel (DF2) in most instances, and at other times on jet fuel (JP8). Each -86 was accompanied by a load bank (Avtron K575), also provided by the USAF for the express purpose of this project.

Flight-line loads on -86s are variable, depending on the aircraft being serviced. In practice, loads are ~10 to 25% capacity (~20 to 50 amps) for F16s, or ~100% (200 amps) for C141s [2,11].

3.2 Emissions-Reduction Technologies

The 6 NOx-reduction technologies evaluated in Phase II of the Green AGE Initiative, and their proponents and locations, were as follows:

- **Dual-Fuel Firing (DFF), BKM, San Diego, CA;**
- **Non-Thermal Discharge (NTD), WL/MNMW, Eglin AFB, FL;**
- **Oxygen-Enriched Air (OEA), AL/CFTS, Brooks AFB, TX;**
- **Selective-Catalytic Reduction (SCR), Houston Industrial Silencing, TX;**
- **Water-in-Fuel Firing (WFF), WL/FIVC, Tyndall AFB, FL; and**
- **NOx-Filter Cart (NFC), AL/EQ, Tyndall AFB, CA.**

Half the technologies, DFF, OEA, and WFF, involved pre-combustion intervention to prevent NOx formation. The other three, NTD, SCR, and NFC, involved post-combustion intervention to either convert (NTD, SCR) or capture (NFC) unabated NOx generated by a -86. Note that NFC was added to the list of technologies to be evaluated after the original selection of 5 in Phase I [2,3].

Each NOx-control technology is discussed briefly next, using information supplied by each technology proponent, and that extracted from the associated technical literature [2-24].

3.2.1 Dual-Fuel Firing (DFF)

In DFF, engine-NOx emissions are reduced in a direct process by cofiring a second fuel having a lower NOx-emission tendency than the baseline liquid-hydrocarbon fuel [7-9]. The typical "dual" fuel is natural gas, which is injected into air-intake valves during diesel-fuel firing in amounts of ~50 to 80% of the normal diesel input.

BKM, Inc., of San Diego, CA, is the proponent of this candidate Green AGE technology. Figure 3.2.1 is a schematic representation of the elements involved with this technology.

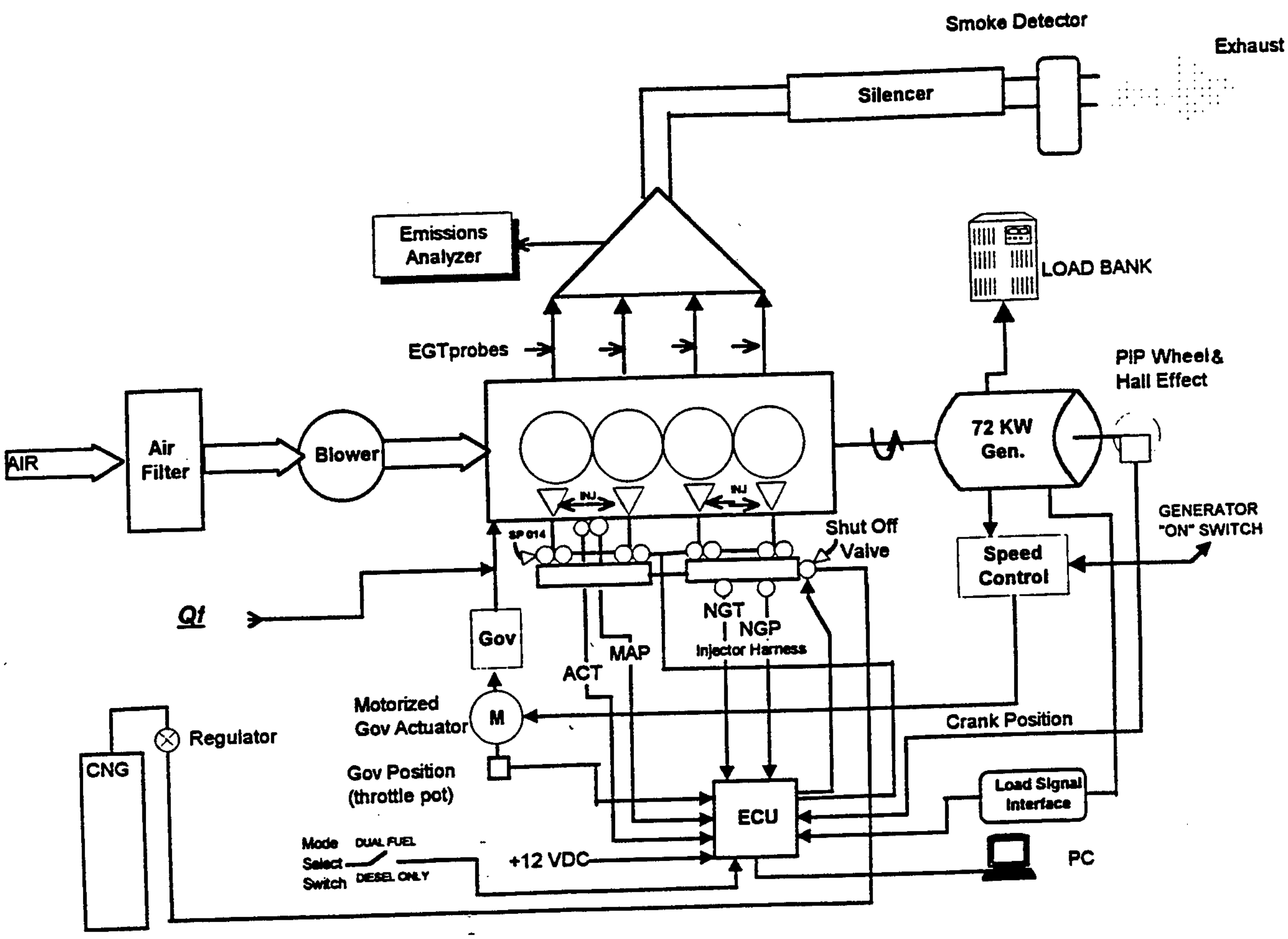


Figure 3.2.1 Dual-Fuel Firing

3.2.2 Non-Thermal Discharge (NTD)

In NTD, NOx is removed from engine exhaust in a 4-step process [11,12]. In the first step, a filter is used to remove particulates from the exhaust. The second step, the principal one, uses a high-dielectric field and a chemical agent (ethanol) to promote the oxidation of NOx in the exhaust to nitrogen dioxide (NO_2) and/or nitric acid (HNO_3). This promotion is accomplished by electrically activating (ionizing) reactants in the oxidation reactions, primarily NO, with the chemical agent. This promotion is electrically, not thermally, driven. In the third step, the NOx-altered exhaust is cooled using a heat exchanger. In the fourth, and last step, a wet scrubber is used to remove the now more water-soluble nitrogenous coproducts from the gaseous-engine exhaust.

The Armament Directorate, Wright Laboratory (WL/MNMW), Eglin AFB, Florida (FL), is the proponent of this candidate Green AGE technology. Figure 3.2.2 is a drawing of this technology.

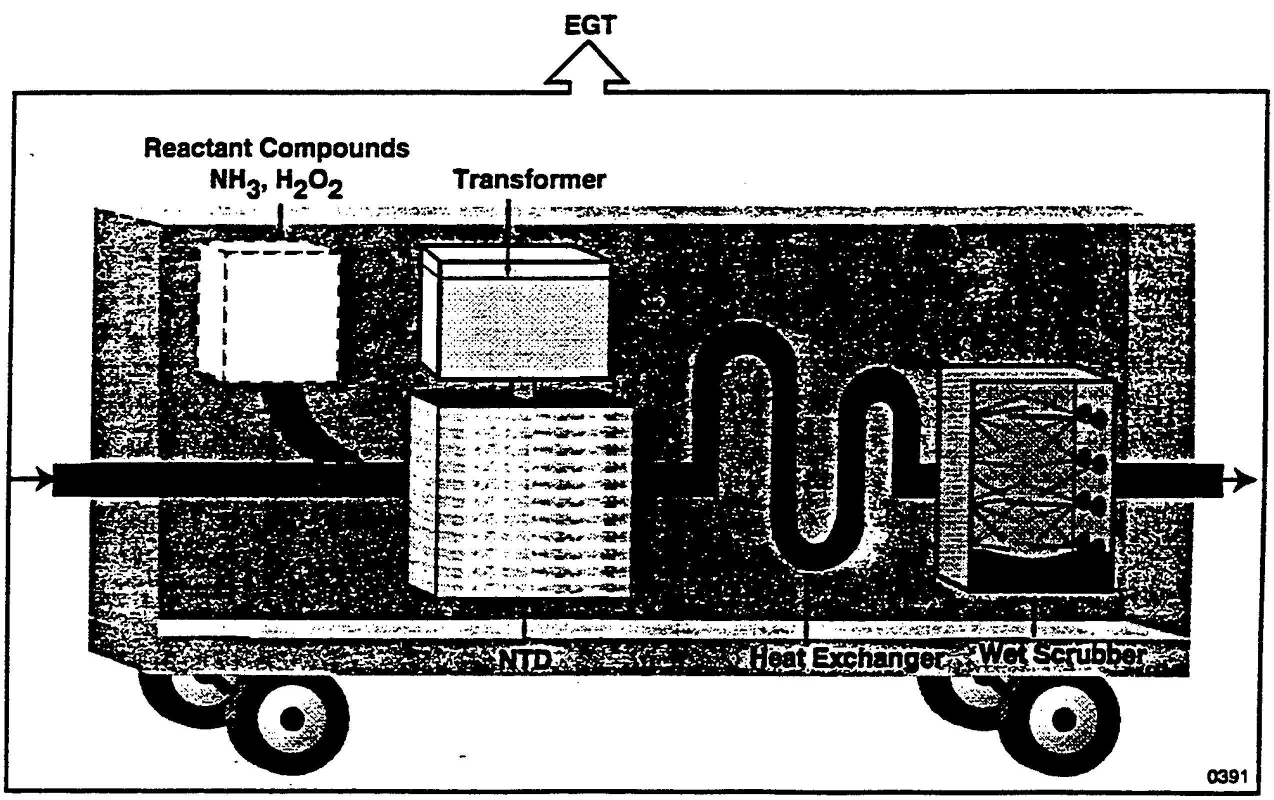


Figure 3.2.2 Non-Thermal Discharge

3.2.3 Oxygen-Enriched Air (OEA)

In OEA, the oxygen content of ambient intake air is increased to levels above ~21%, with the intent of altering combustion in a favorable manner. Oxygen enrichment was to be achieved using a Molecular Sieve Oxygen-Generating System (MSOGS), an existing USAF technology which separates oxygen from nitrogen in air to levels of 99+% purity for use by aerospace crews [15].

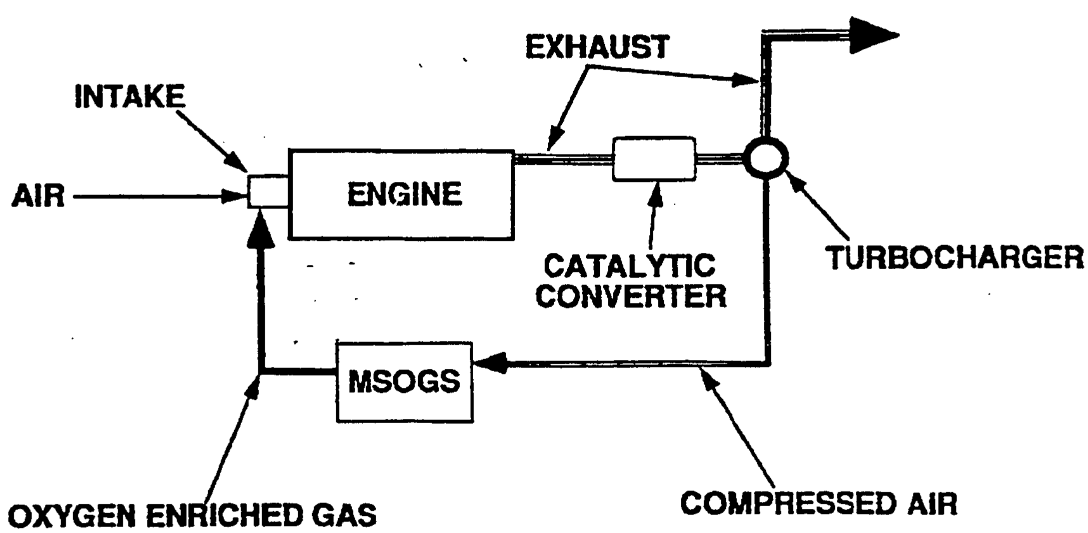
At the outset, it was questionable how OEA would affect -86 NOx emissions, despite tests elsewhere on other diesel engines showing that NOx emissions always increased upon OEA [17,18]. Tests were conducted to discover the actual effect for the -86-specific case.

In the event that OEA failed to reduce NOx directly, the contingency was to combine retarded engine timing (RET) and exhaust gas recirculation (EGR) with OEA to achieve an emissions reduction. In RET, ignition is delayed slightly, causing the normal temperature of internal combustion to be reduced, which in turn, lowers NOx. In EGR, a portion of the engine exhaust is recirculated into the inlet air, lowering its O_2 content and increasing its inert-gas (CO_2) content, both of which cause combustion to proceed at lower temperature, thereby lowering NOx [6,10,16-18].

However, an unwanted consequence of oxygen depletion and thermal inerting from EGR for NOx control is increased carbon monoxide (CO) and particulate (ROx) emission. The contingency was to explore whether slightly elevating the oxygen content of the EGR-treated air, using the MSOGS, could achieve the minimum reduction of NOx, with little or no increase in CO or ROx.

In this report, this hybrid OEA/RET/EGR NOx-reduction technology will be called "OEA".

The Crew Technology Division, Armstrong Laboratory (AL/CFTS), Brooks AFB, Texas (TX), is the proponent of this candidate Green AGE technology. Figure 3.2.3 is a schematic representation of the elements involved with this technology.



3.2.4 Selective-Catalytic Reduction (SCR)

In SCR, NOx is removed from engine exhaust in a 2-step process. In step one, particulates are removed using a filter. In the second, principal, step, a chemical agent (ammonia, NH_3) and a catalyst (vanadia coated onto a titanium-honeycomb support) are used to promote the reduction of NOx to N_2 and water [19]. This promotion is accomplished via the surface catalysis of NOx-reduction reactions, which normally require higher temperatures to proceed to any effective extent.

Houston Industrial Silencing, Houston, TX, is the proponent of this candidate Green AGE technology. Figure 3.2.4 is a schematic representation of the elements involved with this technology.

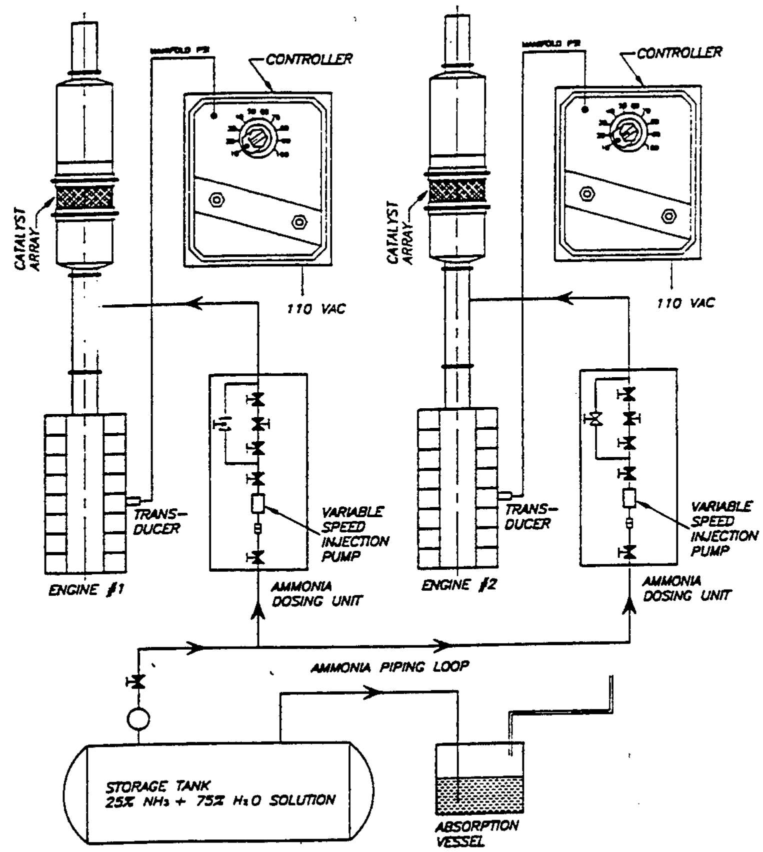


Figure 3.2.4 Selective-Catalytic Reduction

3.2.5 Water-in-Fuel Firing (WFF)

In WFF, water is emulsified with the liquid engine fuel using a surfactant, and then injected through the engine's nozzles [22]. The water in the fuel acts as a heat sink during combustion, lowering temperature, and therefore, reducing the formation of NOx [22,23]. The volumes of water and surfactant needed for emulsification are typically ~30% and ~1%, of the fuel, respectively [23].

The Air Base Technology Branch, Wright Laboratory (WL/FIVC), Tyndall AFB, FL, is the proponent of this candidate Green AGE technology. Figure 3.2.5 is a schematic representation of the elements involved with this technology.

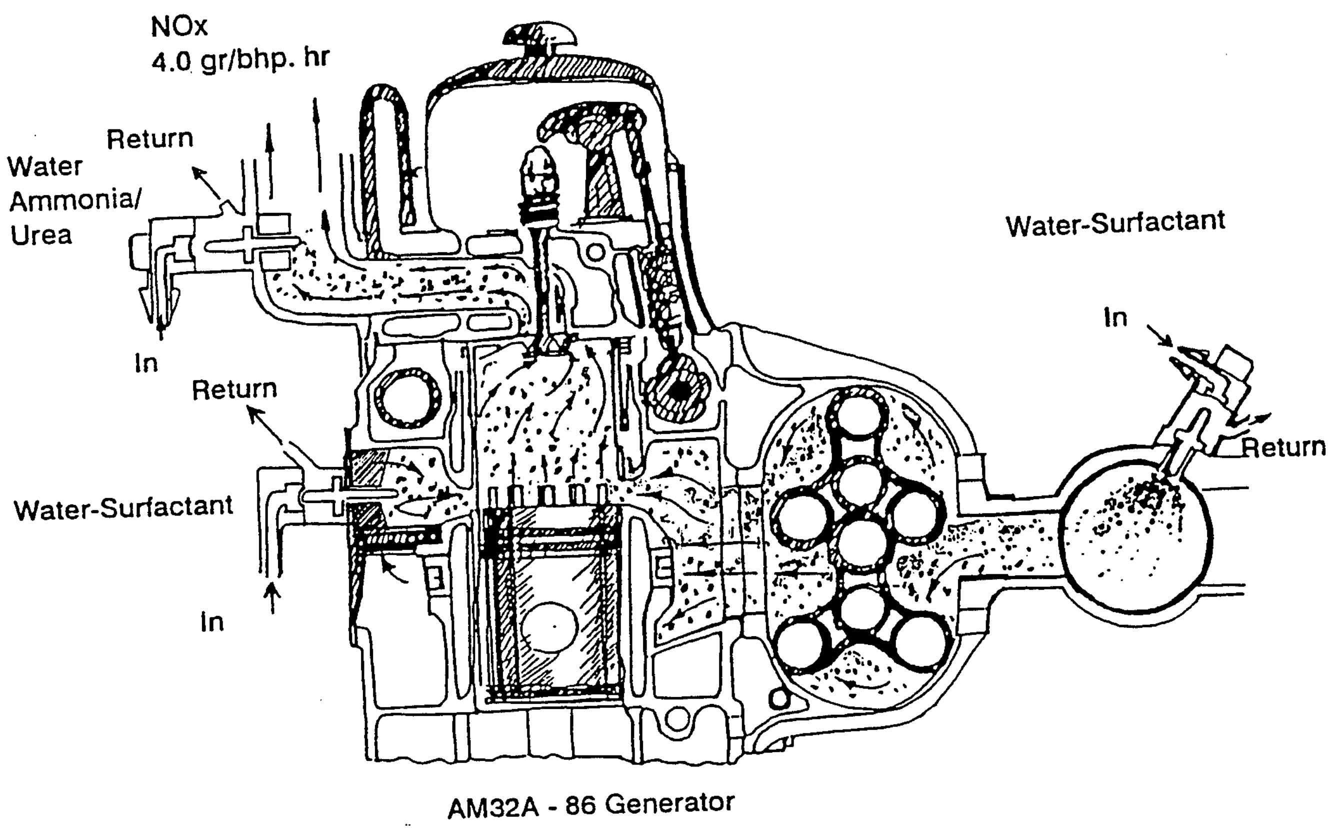


Figure 3.2.5 Water-in-Fuel Firing

3.2.6 NOx-Filter Cart

In NFC, NOx is removed from engine exhaust in a 3-step process. The exhaust is first cooled with an air-to-air heat exchanger, and then filtered to remove particulates. In the third, principal, step, NOx is physically removed (adsorbed) from the cool, particulate-free exhaust using a sorbent filter. The sorbent used in this demonstration was granular activated carbon [24].

The Environics Directorate, Armstrong Laboratory (AL/EQ), Tyndall AFB, FL, is the proponent of this candidate Green AGE technology. Figure 3.2.6 is a photograph of this technology. The device on the left in a -86. The device on the right is the NOx-filter cart. On the left of the NOx-filter cart is the particulate-filter trap; on top is the heat exchanger.

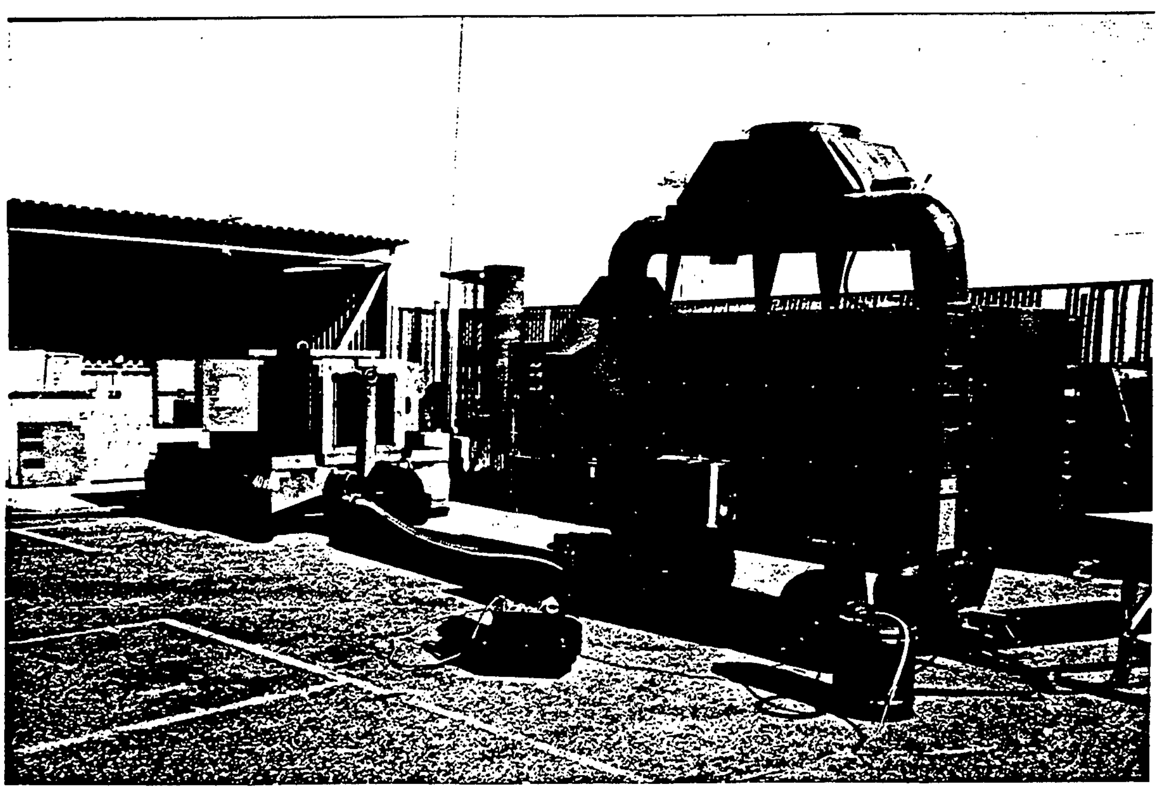


Figure 3.2.6 NOx-Filter Cart

4.0 EVALUATION OF TECHNOLOGIES

The Rating System developed used a 5-criteria, 28-element,100-point scoring plan, as follows:

Emissions Reduction: 25 points (6 elements),
Cost: 25 points (2 elements),
Reliability/Maintainability: 20 points (9 elements),
Deployability: 20 points (8 elements), and
Fidelity of Data: 10 points (3 elements).

Points within each criterion were distributed among individual elements. Each element, and its point value, will be discussed in subsequent sections; they are also presented in Appendix 1.

The focus of this proof-of-concept demonstration was **NOx Reduction**. During Green AGE Phase II, the target NOx reduction became uncertain. The eventual reduction will depend upon which federal and/or state regulation becomes controlling. NOx rules and reductions are discussed next.

At the outset of the Green AGE Initiative, the target NOx reduction was ~70% [2]. This value was estimated using the NOx emissions from an "average March AFB AGE", ~13 grams per brake horsepower-hour (g/bhp-hr), reduced to NOx of 4 g/bhp-hr, as specified by the pending Federal Implementation Plan (FIP). Compliance with this FIP was expected to be necessary as early as 1997.

On the local level, pending SCAQMD regulations require more stringent NOx control [1-3,11]. Under Rule 1110.2 (1990), at full load, internal-combustion engines of ≥50 bhp must emit ≤45 ppm NOx at 15% oxygen (O_2), or alternatively, ≤1.5 g/bhp-hr. Tests on -86s at full load (200 amps) by Pacific Environmental Services (4 units) and Battelle (6 units) indicate that, on average, a -86 emits ~1600 ppm NOx at 15% O_2, or 7.3 g/bhp-hr [4,5]. Hence, a NOx reduction of ~80 to ~95% would be necessary, by December 31, 1999, for March AFB to comply with SCAQMD Rule 1110.2.

In 1993, RECLAIM (Regional Clean Air Incentives Market) was proposed as a replacement to SCAQMD Rule 1110.2. Pending its approval by the EPA, RECLAIM would require March AFB to reduce its total (1995) NOx emissions of ~55 tons to ~13 tons, or a ~75% reduction by the year 2000 [2]. Because they are major NOx emitters, -86s would be the prime targets for NOx-control [11].

The latest regulation possibly governing March AFB is the Morissey Bill, enacted September 1995, by which any portable military AGE is no longer subject to ANY environmental regulation [3].

In summary, target NOx reductions for -86s at March AFB ranged from 0%, to ~70-95%. In the interest of preserving the environment, the USAF sought an NOx reduction of ≥70% [2,3].

4.1 Emissions Reduction

The **Emissions Reductions** criterion was delineated by 6 elements, each described next.

4.1.1 NOx Reduction

Because it was the desired effect, **NOx Reduction** was given the highest point value of any of the 6 elements (10). Points were scored based on comparative NOx reductions demonstrated by each technology. Technologies achieving ≥90% reduction over all loads earned maximum points, followed by those achieving reductions in the 80% (8 points) and 70%-range (5 points) over all loads. Points were prorated for reductions >69% that varied with load. NOx reductions ≤69% scored 0.

Table 4.1.1 lists the NOx Reductions demonstrated, and the scoring (see Appendix 2) [5].

TABLE 4.1.1 NOx REDUCTION

Green AGE TECHNOLOGY	**NOx Reductions (%) @ -86 Loadings**			**Points Scored Out of 10**
	0 Amps	100 Amps	200 Amps	
Dual-Fuel Firing	**ND**	50	50	0
Non-Thermal Discharge	92	70	**ND**	6
Oxygen-Enriched Air	50	**ND**	**ND**	0
Selective-Catalytic Reduction	22	30	96	5
Water-in-Fuel Firing	95	92	85	10
NOx-Filter Cart	100	94	**ND**	8

WFF scored 10 points, because it achieved the highest NOx reductions (≥85%) at all loads. NFC scored 2 less than WFF because, although it achieved high (>90%) reductions, it was not demonstrated (**ND**) at 200 amps. NTD scored 6 points because, although it achieved ≥70% NOx reductions, it was demonstrated on only 10% of a -86s exhaust. SCR scored 5 points, because it demonstrated a >70% reduction at only one load. DFF and OEA each scored 0 points, because they never achieved the 70%-minimum reduction. In DFF tests, the first ~10% NOx reduction resulted from ~5° retarded engine timing (RET), not from DFF. Upon the use of OEA, NOx emissions increased. In "modified" OEA tests, a ~25% NOx reduction resulted from ~5° RET, and the balance from ~30% exhaust gas recirculation (EGR).

4.1.2 Impact on CO

The next element assessed the impact of NOx reduction on the emission of carbon monoxide, CO, another criteria pollutant, one for which March AFB is in compliance with Rule 1110.2 [4]. By compliant is meant that current -86 CO emissions are ≤2000 ppm at 15% O_2 [1,4].

Points were awarded based on how NOx-control impacted baseline CO emissions. Maximum points (3) were awarded if NOx-control reduced CO; 2 points if there were no effect; 1 point if CO increased, but to a still-compliant level; and 0 points if CO increased to a non-compliant level.

Table 4.1.2 lists the changes in CO observed upon NOx reduction, and the scoring. CO data were taken at the same loads reported for the NOx reductions (see Table 4.1.1 and Appendix 2) [5].

TABLE 4.1.2 IMPACT ON CO

Green AGE Technology	Impact on CO	Points Scored Out of 3
Dual-Fuel Firing	Increase to non-compliant levels	0
Non-Thermal Discharge	Increase, but to compliant levels	1
Oxygen-Enriched Air	No change	2
Selective-Catalytic Reduction	Reduction	3
Water-in-Fuel Firing	Decrease, or increase to non-compliant levels	1
NOx-Filter Cart	Reduction	3

DFF scored 0 points, because it caused dramatic increases in CO (factors of >5) at each load tested (100 and 200 amps) [8]. Such an increase upon DFF has been observed elsewhere [9].

NTD scored 1 point because, at the loads tested (0 and 100 amps), it caused modest increases in CO emissions, which remained in compliance with SCAQMD Rule 1110.2 [12].

OEA (plus RET and EGR) scored 2 points, because its combined effect caused CO emissions to remain unchanged, but only at the one load tested (0 amps) [16].

SCR scored maximum (3) points, because it resulted in CO reductions of ~5% to ~95% at all the loads tested (0, 100, and 200 amps) [5].

WFF increased CO emissions at 0 and 100 amps (by factors of >4), but decreased CO emissions (by ~50%) at 200 amps [23]. It was therefore awarded 1 point.

NFC was awarded 3 points for nearly quantitative (~100%) CO reductions at the loads tested (0 and 100 amps) [24].

4.1.3 Impact on ROx

The next element involved the impact of NOx reduction on the emission of particulates, ROx, another criteria pollutant which was in compliance with SCAQMD Rule 1110.2 at March AFB [1,4].

Points were awarded based on how NOx-control impacted baseline ROx emissions. Maximum points (3) were awarded if the NOx-control technology itself reduced ROx; 2 points if there was no effect on ROx; 1 point if an ancillary component (namely, a filter), required to implement the NOx-control technology reduced ROx; and 0 points if ROx increased.

Table 4.1.3 lists the changes in ROx observed upon NOx reduction, and the scoring. ROx data were taken at the same loads reported for the NOx reductions (see Table 4.1.1).

TABLE 4.1.3 IMPACT ON ROx

Green AGE Technology	Impact on ROx	Points Scored Out of 3
Dual-Fuel Firing	Decrease, because of DFF technology	3
Non-Thermal Discharge	Decrease, but because of prefilter	1
Oxygen-Enriched Air	Decrease, because of OEA technology	3
Selective-Catalytic Reduction	Decrease, but because of prefilter	1
Water-in-Fuel Firing	Decrease, because of WFF technology	3
NOx-Filter Cart	Decrease, but because of prefilter	1

DFF, OEA, and WFF demonstrated inherent reductions in ROx emissions, and were, therefore each awarded maximum points (3). This effect has been observed elsewhere [6,9,10,17,18].

NTD, SCR, and NFC require prefiltering of -86 exhaust (particulate trap) prior to the -86 exhaust entering the NTD reactor, the catalysis bed, or the sorbent filter, respectively [12,19,24]. Because a reduction in ROx was required to attempt the NOx reduction, NTD, SCR, and NFC were each awarded 1 point.

4.1.4 Impact on RHC

The next element assessed the impact of NOx reduction on the baseline emission of reactive hydrocarbons, RHC, another criteria pollutant. RHC emissions were in compliance with SCAQMD Rule 1110.2 at March AFB: ≤250 ppm at 15% O_2, measured as methane [1,4].

Points were awarded based on how NOx-control impacted baseline RHC emissions. Maximum points (3) were awarded if the NOx-control technology reduced RHC; 2 points if there was no effect; 1 point if an ancillary component (namely, another process) required to implement the NOx-control technology reduced RHC; and 0 points if RHC emissions increased.

Table 4.1.4 lists the changes in RHC observed upon NOx reduction, and the scoring. RHC data were taken at the same loads reported for the NOx reductions (see Table 4.1.1) [5].

TABLE 4.1.4 IMPACT ON RHC

Green AGE Technology	Impact on RHC	Points Scored Out of 3
Dual-Fuel Firing	Increase to non-compliant levels	0
Non-Thermal Discharge	No change	2
Oxygen-Enriched Air	Decrease, because of OEA technology	3
Selective-Catalytic Reduction	No change	2
Water-in-Fuel Firing	Increase to non-compliant levels	0
NOx-Filter Cart	Decrease, because of NFC technology	3

In DFF, the timing of dual-fuel injection during air intake was such that the exhaust valve was open at the same time, allowing some injected natural gas to escape [8,9]. This problem may be inherent to DFF in 2-stroke engines, such as the -86. Therefore, DFF scored 0 points.

In NTD, because there was no change in RHC emissions, 2 points were awarded. However, this effect was demonstrated on only ~10% of the total -86 exhaust [12].

In OEA, added oxygen in the EGR allowed hydrocarbon fuel-combustion to be more complete, thereby reducing RHC emissions [16]. OEA was therefore awarded maximum (3) points.

In SCR, 2 points were awarded, because of the neutral effect on RHC emissions [19].

In WFF, 0 points were awarded, because RHC emissions increased, as expected [10].

In NFC, maximum points (3) were awarded, because RHC emissions were effectively adsorbed along with the NOx and CO, as expected [24].

4.1.5 Secondary Emissions

The next element assessed whether the NOx-reduction technology caused the emission of a new, or "secondary", pollutant. From a review of the candidate technologies, the secondary emission of methane (CH_4), ethanol (C_2H_5OH), ammonia (NH_3), ozone (O_3), or O_2 was considered possible.

Maximum points (3) were awarded if no secondary emission could take place. Two points were awarded if there were a possibility that any secondary emission could take place. One point was awarded if any secondary emission was expected to take place. Zero points were given if any secondary pollutant was emitted at an unacceptable level.

Table 4.1.5 lists the possibilities of Secondary Emission occurring, and the scoring.

TABLE 4.1.5 SECONDARY EMISSIONS

Green AGE Technology	Secondary Emissions	Points Scored Out of 3
Dual-Fuel Firing	Fugitive natural gas	2
Non-Thermal Discharge	Fugitive ethanol, ozone	2
Oxygen-Enriched Air	Fugitive oxygen	2
Selective-Catalytic Reduction	Fugitive ammonia	1
Water-in-Fuel Firing	None	3
NOx-Filter Cart	None	3

Because they do not require additional gaseous chemicals to perform, WFF and NFC were each awarded maximum points (3), because secondary emission is not possible.

Although difficult to prove either way, assumed in this evaluation was that there was a possibility for secondary emissions taking place during DFF, NTD, and OEA. Each of these candidate Green AGE technology was therefore awarded 2 points.

For DFF, natural-gas leaks could create both environmental and fire-safety problems.

For NTD, release of ethanol or ozone could create both environmental and health problems.

For OEA, oxygen release could create a fire-safety hazard.

For SCR, ammonia "slippage" (5-20 ppm) is a reality [19]. SCR therefore scored 1 point.

4.1.6 Deployment Schedule

The last element assessed when the NOx-reduction technology could be deployed on -86s. Deadlines in the FIP, SCAQMD Rule 1110.2, and the Clean Air Act may require the deployment of NOx-control technologies at March AFB any time between now and the turn of the century [1,2].

Scores of 3, 2, or 1 point(s) were awarded if deployment could take place by either the end of 1997, 1998, or 1999, respectively. If the technology were not deployable by 2000, its score was 0.

Table 4.1.6 lists the anticipated Deployment Schedules, and the scoring.

TABLE 4.1.6 DEPLOYMENT SCHEDULE

Green AGE Technology	Deployment Schedule	Points Scored Out of 3
Dual-Fuel Firing	Technology in practice elsewhere	3
Non-Thermal Discharge	Technology not in practice	0
Oxygen-Enriched Air	Components in practice elsewhere	1
Selective-Catalytic Reduction	Technology in practice	3
Water-in-Fuel Firing	Technology in practice	3
NOx-Filter Cart	Components in practice elsewhere	2

DFF, SCR and WFF are NOx-reduction technologies that have been designed, field-tested, deployed, and sold commercially on either engines or other types of combustors. Each was therefore awarded maximum points (3).

Because of its relative simplicity, NFC appears ready for deployment on a technical basis. As will be discussed later, NFC may not be deployable now because of other issues. These issues, could, however, be resolved in 1-2 years of testing. NFC was therefore awarded 2 points.

Although OEA has been deployed in different combustion systems, the intent has been for the reduction of CO, ROx, and RHC, rather than NOx emissions, which it increases. However, the emissions-control techniques used to supplement OEA, namely RET and EGR, have both been commercialized. For these reasons, "OEA" was awarded 1 point.

Compared to all the other candidate Green AGE technologies, NTD is in the early stages of development [11,12]. This infancy is illustrated by the fact that NTD was the only technology of the 6 not to be demonstrated on the full exhaust of a -86. For this reason, NTD was awarded 0 points.

4.1.7 Summary on Emissions Reduction

Table 4.1.7 lists the scoring of each candidate Green AGE technology in terms of the 6 elements of the Emissions Reduction criterion. As indicated, WFF and NFC tied for the top place, followed by SCR, NTD, OEA, and DFF.

TABLE 4.1.7 EMISSIONS-REDUCTION RATING

Green AGE Technology	Points Scored (25 maximum)	Relative Ranking
Dual-Fuel Firing	8	5
Non-Thermal Discharge	12	3
Oxygen-Enriched Air	11	4
Selective-Catalytic Reduction	15	2
Water-in-Fuel Firing	20	1
NOx-Filter Cart	20	1

Efforts were undertaken to determine the confidence with which this weighted ranking was discriminating. This methodology will be discussed in the summary of each Rating Criterion.

First, at the outset of the program, the 6 technologies were informally evaluated using the Rating System, and information provided by proponents and opponents. Scores ranged from 4 to 19 out of 25, with an average of 13. The span and distribution of these first-order scores indicated that the Rating System was sufficiently discriminating for evaluation purposes (see Appendix 1).

Now that proof-of-concept demonstrations are complete, the same Rating System yields a range of scores of 8 to 20 out of 25, with an average of 14. Without needing to reveal the details, the relative ranking of the 6 technologies changed somewhat since that first, informal ranking. Hence, the more complete and better defined information gathered during the proof-of-concept demonstrations had an impact on this technical evaluation. The NOx reductions that could be demonstrated made this difference. Original estimates for NOx reduction were optimistic.

Second, to determine the variability in ratings for the Emissions Reduction criterion, each technology was scored by 3 different engineers. The variability in any total score was ± 1 point. This variability is not enough to alter the relative rankings of the 6 technologies, which can be viewed, from an Emissions-Reduction viewpoint, as consisting of 4 groupings: WFF and NTD in a first one; SCR in a second one; NTD and OEA in a third; and DFF in a last one.

Other rating elements are now used to further discriminate the merit of the technologies.

4.2 Cost

The "Cost" criterion was delineated by 2 elements, each described next.

4.2.1 Capital Costs

The first Cost element, "Capital Costs", was given a 10-point maximum value. The methodology was a simple arithmetic analysis. The technology with the lowest apparent capital cost for NOx control received maximum points. The other technologies were scored proportionately, relative to the lowest cost, with the highest-cost technology receiving the least, or 0, points.

Table 4.2.1 presents the scores for the comparative analysis of Capital Cost. The data used were those reported by each Green AGE technology proponent [2,3,7,12,15,19,22,24].

TABLE 4.2.1 CAPITAL COSTS

Green AGE Technology	Capital Costs	Points Scored Out of 10
Dual-Fuel Firing	~$ 6K per unit	1
Non-Thermal Discharge	~$40K per unit	0
Oxygen-Enriched Air	~$1.5K per unit	5
Selective-Catalytic Reduction	~$ 5K per unit	2
Water-in-Fuel Firing	~$0.8K per unit	10
NOx-Filter Cart	~$12K per unit	1

Because the estimated capital cost for WFF was lowest, it was awarded maximum points (10). This capital cost covered the larger fuel injectors required, plus the fuel-emulsification equipment.

The next lowest estimated capital cost was for OEA. This cost was based on coupling a -86 with a MSOGS for OEA, RET, and EGR. By virtue of its being about twice the capital cost per unit of WFF, 5 points were awarded.

Finally, by virtue of their being about an order-of-magnitude, or more, higher in capital cost per unit than WFF or OEA, DFF, SCR, NFC, and NTD scored between 0 and 2 points. Capital costs for these technologies are much higher per unit, because of the need for additional hardware: catalysts (SCR); electronics (DFF, NTD); heat exchangers (NTD, NFC); filters (SCR, NFC, NTD); and wet scrubbers (NTD).

4.2.2 Operating Costs

The second Cost element, "Operating Costs", was given a 15-point maximum value. Again, the methodology was a simple arithmetic analysis. The technology with the lowest apparent operating cost for NOx control received maximum points. The other technologies were scored proportionately, relative to the lowest cost, with the highest-cost technology receiving the least points.

Table 4.2.2 presents the scores for the comparative analysis of Operating Cost. The data used were those reported by each Green AGE technology proponent [2,3,7,12,15,19,22,24].

TABLE 4.2.2 OPERATING COSTS

Green AGE Technology	Operating Costs	Points Scored Out of 15
Dual-Fuel Firing	~$150 per unit	5
Non-Thermal Discharge	~$600 per unit	1
Oxygen-Enriched Air	~$ 85 per unit	9
Selective-Catalytic Reduction	~$ 50 per unit	15
Water-in-Fuel Firing	~$150 per unit	5
NOx-Filter Cart	~$150 per unit	5

Because the operating cost for SCR was lowest, it was awarded maximum points (15). This cost primarily covered the cost of the ammonia NOx-reducing agent.

The next lowest estimated operating cost was for OEA. This cost was essentially the cost of operating a MSOGS. By being ~1.7-times higher in operating cost than SCR, 9 points were awarded.

By virtue of their being ~3 times higher in operating cost than SCR per unit, DFF, WFF, and NFC each scored 5 points. Operating costs for DFF, WFF, and NFC are higher because of the need to use natural-gas as a fuel, surfactants for emulsification, and filters for emissions capture, respectively. WFF also results in a ~2-3% loss in fuel economy (greater fuel consumption).

The operating cost of NTD was highest, primarily because of its complexity, and the unresolved issue of electrode durability (damage to plates and their coating). NTD was awarded 1 point for its relatively high operating cost.

4.2.3 Summary on Costs

Table 4.2.3 lists the scoring of each candidate Green AGE technology in terms of the 2 elements of the Cost criterion. As indicated, SCR was in the top place, followed by WFF in second OEA in third, DFF and NFC in forth, and NTD in last place.

TABLE 4.2.3 COST RATING

Green AGE Technology	Points Scored (25 maximum)	Relative Ranking
Dual-Fuel Firing	6	4
Non-Thermal Discharge	1	5
Oxygen-Enriched Air	14	3
Selective-Catalytic Reduction	17	1
Water-in-Fuel Firing	15	2
NOx-Filter Cart	6	4

At the outset of the program, the 6 technologies were informally evaluated using the Rating System, and preliminary information provided by proponents and opponents. Scores ranged from 1 to 15 out of 25, with an average of 9. The span and distribution of these first-order scores indicated that the Rating System was sufficiently discriminating for evaluation purposes (see Appendix 1).

After the proof-of-concept demonstrations were completed, the same Rating System yielded similar scores. Hence, the results of Phase II did little to change economic considerations.

To determine the variability in ratings for the Cost criterion, each technology was scored by 3 different engineers. The variability in any total score was ± 1 point. This variability is not enough to alter the relative rankings of the 6 technologies, which can be viewed, from a Cost viewpoint, as consisting of 3 groupings: SCR, WFF, and OEA in one; DFF and NFC in a second, and NTD in a last one.

4.3 Reliability and Maintainability

The "Reliability and Maintainability" criterion was delineated by 9 elements, as follows.

4.3.1 Reliability

The "Reliability" element assessed if a technology reduced emissions "on demand". That is, whether the control technology was "on" upon cold start-up, and was operative at all loads.

Maximum points (2) were scored if the technology had maximum effectiveness "on demand". One point was scored if the technology were operative at idle and one load. No points were scored if the technology needed a warmup time, or a load, before it effectively reduced NOx emissions.

Table 4.3.1 lists the assessment of Reliability, along with the scoring.

TABLE 4.3.1 RELIABILITY

Green AGE Technology	Reliability	Points Scored Out of 2
Dual-Fuel Firing	Not on at idle, effective at load	0
Non-Thermal Discharge	Operation decreases with load	1
Oxygen-Enriched Air	Not operative at medium, full load	1
Selective-Catalytic Reduction	Not effective on start up/low load	0
Water-in-Fuel Firing	Operative on start up and all loads	2
NOx-Filter Cart	Not operative at full load	1

WFF was the only technology operative on demand, and effective at all -86 loads, and therefore scored maximum (2) points.

NTD, OEA, and NFC each scored 1 point, because their ability to operate diminished or ceased as load increased. In NTD, the limiting condition was too high a temperature, which must be reduced via heat exchanging. In the case of OEA, the limiting condition was the amount of EGR that could be used before engine operation deteriorated. For NFC, the limiting condition was too high a temperature as load increased, as well as the saturation capacity of the sorbent filters.

DFF and SCR each scored 0 points. For DFF, natural gas can not be used to reduce NOx upon startup because of the need for diesel fuel for (compression) ignition. SCR scored 0 points because of the need to preheat the catalyst, and to expose it to the highest possible exhaust temperature the -86 could generate. That is, for SCR, the limitation is too low a temperature.

4.3.2 Maintainability of -86

Maintainability was divided into 2 elements, with one being for the -86 generator, and the other for the emissions-reduction technology (next section).

Maximum points (2) were awarded for the technology expected to result in a lower number of service hours for the -86. Technologies requiring more service and maintenance than -86s normally require received less points.

Table 4.3.2 lists the assessment of -86 Maintainability, along with the scoring.

TABLE 4.3.2 MAINTAINABILITY OF -86

Green AGE Technology	Maintainability of -86	Points Scored Out of 2
Dual-Fuel Firing	Timing adjustments	1
Non-Thermal Discharge	Not part of engine	2
Oxygen-Enriched Air	Possible corrosion	1
Selective-Catalytic Reduction	Not part of engine	2
Water-in-Fuel Firing	Possible corrosion	1
NOx-Filter Cart	Not part of engine	2

NTD, SCR, and NFC each scored maximum (2) points, because, as post-combustion emissions-control technologies, they are not expected to influence normal -86 operation, with the exception of some effect because of the back-pressure they may exert.

DFF scored 1 point, because of the need to maintain the timing of injected natural gas. This drawback was countered by the claim that cofiring a diesel engine with some natural gas might require less engine maintenance than neat diesel-fuel firing [8].

Both OEA and WFF each scored 1 point, because the use of EGR (OEA) or an emulsified fuel, respectively, may result in engine corrosion, which would increase engine maintenance [9,23]. For this reason, a corrosion inhibitor is usually part of the "surfactant package" for WFF.

4.3.3 Maintainability of Technology

The other "Maintainability" element was for the emissions-reduction technology alone.

Maximum points (2) were awarded for the technology expected to require the lowest number of service hours. Technologies requiring more maintenance than this minimum received less points.

Table 4.3.3 lists the assessment of Maintainability of Technology, along with the scoring.

TABLE 4.3.3 MAINTAINABILITY OF TECHNOLOGY

Green AGE Technology	Maintainability of Technology	Points Scored Out of 2
Dual-Fuel Firing	Least complicated	2
Non-Thermal Discharge	Most complicated	0
Oxygen-Enriched Air	MSOGS maintenance	1
Selective-Catalytic Reduction	Ammonia-injection control	1
Water-in-Fuel Firing	Fuel/water emulsion quality	1
NOx-Filter Cart	Sorbent replacement	0

DFF scored maximum (2) points, because it consists of a relatively maintenance-free injectors and accompanying electronic control package. The compressed natural-gas supply system is also relatively maintenance free.

OEA, SCR, and WFF scored 1 less point than DFF, because they are more complicated. For OEA, a MSOGS must be maintained along with the -86. For SCR, the ammonia-injection system will require close, periodic inspection and maintenance to ensure that ammonia does not "slip". Moreover, frequent on/off use of the -86 may result in the separation of catalyst from its support. For WFF, the quality of the fuel/water emulsion must be checked regularly, especially during periods of storage, and -86 non-use. Moreover, the quality of the water used may also need to be checked.

NTD and NFC were each awarded 0 points. NTD admittedly has fragile reactor components (electrodes), and may not be as resistant to transport as a -86. The sorbent filters in NFC also may not be very transportable. As such, more care and maintenance may be required for each.

4.3.4 Functionality

"Functionality" assessed the power needs of the emissions-reduction technology.

Those emissions-reduction technologies requiring no -86 power earned 2 points. Those requiring some power from the -86 during NOx control earned 1 point. Those requiring extensive power earned 0 points.

Table 4.3.4 lists the assessment of Functionality, along with the scoring.

TABLE 4.3.4 FUNCTIONALITY

Green AGE Technology	Functionality	Points Scored Out of 2
Dual-Fuel Firing	Electrically dependent	1
Non-Thermal Discharge	Very electrically dependent	0
Oxygen-Enriched Air	Very electrically dependent	0
Selective-Catalytic Reduction	Electrically dependent	1
Water-in-Fuel Firing	Electrically independent	2
NOx-Filter Cart	Electrically dependent	1

WFF was awarded 2 points, because it requires no electricity to reduce NOx from a -86.

DFF, SCR, and NFC were each awarded 1 point, because each requires some electricity during NOx reduction. For DFF, electricity is needed for the injectors and electronic control unit. For SCR, electricity is needed for the ammonia-injection system, and possibly a catalyst-bed heater. For NFC, electricity is needed for the heat exchanger.

OEA and NTD were each awarded 0 points, because each was more electrically dependent than the other emission-reduction technologies. In OEA, a turbocharger is needed to operate the MSOGS. In NTD, 3 kW of the 72 kW output of the -86 is needed to operate the NTD reactor, power which must first be conditioned to 12 kV using a high-voltage transformer. Electricity is also needed to operate the pump on the wet scrubber.

4.3.5 Availability of Supplies

"Availability of Supplies" assessed whether components of different NOx-reduction technologies were "off-the-shelf", or had to be "custom made". Two points were awarded if components were off-the-shelf. One point was awarded if they were a combination of off-the-shelf and prototypes. Zero points were awarded if they were exclusively custom components.

Table 4.3.5 lists the assessment of Availability of Supplies, along with the scoring.

TABLE 4.3.5 AVAILABILITY OF SUPPLIES

Green AGE Technology	Availability of Supplies	Points Scored Out of 2
Dual-Fuel Firing	Injectors, ECU: off-the-shelf	2
Non-Thermal Discharge	NTD reactor: custom	0
Oxygen-Enriched Air	EGR system: custom	1
Selective-Catalytic Reduction	SCR system: custom	0
Water-in-Fuel Firing	Emulsion system: custom	1
NOx-Filter Cart	Filter cart: custom	1

DFF scored maximum points, because injectors and control units are off-the-shelf items.

OEA, WFF, and NFC scored 1 point, because of the need to custom-make EGR systems, fuel/water emulsion-preparation systems, and filter carts, respectively. However, MSOGS for OEA, nozzles for WFF, and particulate traps and heat exchangers for NFC are off-the-shelf items.

SCR and NTD each scored 0 points, because each are custom-built systems. For SCR, the catalyst and support must be specially sized and fabricated for deployment on a -86. Moreover, catalyst availability might also be a problem.

For NTD, the reactor is "novel" equipment, compared to that for the other technologies. The filter, heat exchanger, and wet scrubber needed for NTD are, however, off-the-shelf items.

4.3.6 Feasibility

"Feasibility" assessed whether demonstration of the technology was achieved on the full exhaust of a -86, which is 380 $\pm$ 16 dry standard cubic feet per minute at 50 to 200 amps [4].

Maximum (2) points were awarded if the proof-of-concept unit "processed" the entire exhaust. Zero points were awarded if the technology, in its current state, processed less than full capacity.

Table 4.3.6 lists the assessment of Feasibility, along with the scoring.

TABLE 4.3.6 FEASIBILITY

Green AGE Technology	Feasibility	Points Scored Out of 2
Dual-Fuel Firing	Full exhaust processed	2
Non-Thermal Discharge	Partial exhaust processed	0
Oxygen-Enriched Air	Full exhaust processed	2
Selective-Catalytic Reduction	Full exhaust processed	2
Water-in-Fuel Firing	Full exhaust processed	2
NOx-Filter Cart	Full exhaust processed	2

DFF, OEA, SCR, WFF, and NFC were each demonstrated at full -86 exhaust capacity, and were therefore awarded maximum (2) points.

Only NTD was not demonstrated on the full -86 exhaust, and therefore scored 0 points. NTD was demonstrated on only $\sim 10\%$ of the exhaust of a -86.

4.3.7 Safety of -86 Operation

"Safety of -86 Operation" assessed whether the normal operation of a -86 was made more dangerous by the use of an emissions-reduction technology. Risks, such as those posed by use of high-voltages, or compressed oxygen, natural gas, or ammonia, were envisioned.

Maximum points (4) were awarded if -86 safety were not compromised by the operation of an emissions-reduction technology. Fewer points were awarded the more new hazards were posed.

Table 4.3.7 lists the assessment of Safety of -86 Operation, along with the scoring.

TABLE 4.3.7 SAFETY OF -86 OPERATION

Green AGE Technology	Safety of -86 Operation	Points Scored Out of 4
Dual-Fuel Firing	Compressed-gas hazard	2
Non-Thermal Discharge	Electrical hazard	1
Oxygen-Enriched Air	Compressed oxygen hazard	2
Selective-Catalytic Reduction	Ammonia hazard	2
Water-in-Fuel Firing	Fuel is less of hazard	4
NOx-Filter Cart	Fugitive dust, filter-fire hazard	3

WFF was awarded maximum (4) points, because it created an operating environment during NOx reduction that was at least as safe, and may be safer, than the existing one. By safer is meant that the emulsified fuel would be less prone to ignition than the neat diesel or jet fuels. The surfactant used to prepare the emulsion is also non hazardous.

NFC was awarded 1 point less than WFF, because it appears to be almost as safe to implement as WFF. The only new dangers suggested might be exposure to sorbent dust during maintenance, and the remote possibility of the sorbent spontaneously igniting, if exposed to high moisture levels.

DFF, OEA, and SCR each scored 2 points, because each introduces a potentially new hazard to normal -86 operation. In the case of all, there is a new risk posed by the presence, possibly in compressed (high-pressure) form, of natural gas for DFF, oxygen for OEA, and ammonia for SCR.

NTD scored the least points (1) because, in addition to potentially new hazards posed by the use of additional chemicals (ethanol, sodium hydroxide), a potential electrical hazard may exist.

4.3.8 Life-Cycle of Materials

"Life-Cycle of Materials" assessed any added environmental pollution responsibility the emission-reduction technology might bring to -86 operation.

Technologies that used recyclable materials earned maximum (2) points. Technologies that had the potential to produce new hazardous wastes during their deployment earned less points.

Table 4.3.8 lists the assessment of Life-Cycle of Materials, along with the scoring.

TABLE 4.3.8 LIFE-CYCLE OF MATERIALS

Green AGE Technology	Life-Cycle of Materials	Points Scored Out of 2
Dual-Fuel Firing	Environmentally benign	2
Non-Thermal Discharge	Disposal of scrub water	1
Oxygen-Enriched Air	Disposal of molecular sieve material	1
Selective-Catalytic Reduction	Disposal of spent catalyst	1
Water-in-Fuel Firing	Environmentally benign	2
NOx-Filter Cart	Disposal of sorbent	1

DFF and WFF each scored maximum (2) points. In both DFF and WFF, the "modified" fuels used to cause NOx reduction can be disposed of via direct combustion in the -86. In WFF, the surfactant is biodegradable.

NTD, OEA, SCR, and NFC each scored 1 point, because a new "waste disposal" problem may be created: acidic water from the scrubber from NTD; MSOGS membranes from OEA; deactivated catalyst from SCR; and NOx-saturated sorbent from NFC. One point, and not zero points, was awarded each because the potential wastes generated by each can probably be "handled" by commercial treatment technologies.

4.3.9 Training

The last element of the Reliability and Maintainability criterion assessed the new "Training" a flight-line crew would require to operate a -86 generator with reduced emissions.

The lower the additional training hours anticipated, the more points earned (up to 2).

Table 4.3.9 lists the assessment of Training, along with the scoring.

TABLE 4.3.9 TRAINING

Green AGE Technology	Training	Points Scored Out of 2
Dual-Fuel Firing	Compressed natural-gas handling	1
Non-Thermal Discharge	Reactor, scrubber operation	0
Oxygen-Enriched Air	MSOGS operation	1
Selective-Catalytic Reduction	Ammonia handling	1
Water-in-Fuel Firing	Fuel/water preparation; nozzle replacement	1
NOx-Filter Cart	Filter replacement	1

As Table 4.3.9 indicates, each candidate NOx-control technology will require flight-line crews to learn some new skills to operate a "green" -86. With the exception of NTD, the new training should be straightforward, because the new tasks consist of relatively standard procedures.

NTD scored the least (0) points, because it has the greatest number of new components, with the central one, the reactor, not having a standard operating procedure established. Moreover, NTD would introduce the greatest number of "new and different" equipment to flight-line operation: NTD reactor and wet scrubber.

4.3.10 Summary on Reliability and Maintainability

Table 4.3.10 lists the scoring of each candidate Green AGE technology in terms of the 9 elements of the Reliability and Maintainability criterion. As indicated, WFF was first, followed by DFF, NFC, OEA and SCR, and then NTD.

TABLE 4.3.10 RELIABILITY AND MAINTAINABILITY RATING

Green AGE Technology	Points Scored (20 maximum)	Relative Ranking
Dual-Fuel Firing	13	2
Non-Thermal Discharge	5	5
Oxygen-Enriched Air	10	4
Selective-Catalytic Reduction	10	4
Water-in-Fuel Firing	16	1
NOx-Filter Cart	12	3

At the outset of the program, the 6 technologies were informally evaluated using the Rating System, and information provided by proponents and opponents. Scores ranged from 8 to 17 out of 20, with an average of 13. The span and distribution of these first-order scores indicated that the Rating System was sufficiently discriminating for evaluation purposes (see Appendix 1).

After the proof-of-concept demonstrations were completed, the same Rating System yielded the above scores, which ranged from 5 to 16 out of 20, with an average of 11. Without needing to reveal the details, the relative ranking of the 6 technologies changed somewhat since this first, informal evaluation. Hence, the results of Phase II had an impact on Reliability and Maintainability considerations.

To determine the variability in ratings for the Reliability and Maintainability criterion, each technology was scored by 3 different engineers. The variability in any total score was ± 1 point. This variability is not enough to alter the relative rankings of the 6 technologies, which can be viewed, from an Reliability and Maintainability viewpoint, as consisting of 4 groupings: WFF in one; DFF and NFC in a second; OEA and SCR in a third, and NTD in a last one.

4.4 Deployability

The "Deployability" criterion was delineated by 8 elements, each described next.

4.4.1 Applicability

The first element, "Applicability", assessed if an emissions-reduction technology were specific to the -86, or whether it could be deployed universally on aerospace ground equipment.

Maximum points (3) were given for being universally adaptable. One point was given if the technology were specific to the -86.

Table 4.4.1 lists the assessment of Applicability, along with the scoring.

TABLE 4.4.1 APPLICABILITY

Green AGE Technology	Applicability	Points Scored Out of 3
Dual-Fuel Firing	Only to diesel-engined AGE	1
Non-Thermal Discharge	To any AGE exhaust	3
Oxygen-Enriched Air	Only to diesel-fired AGE	1
Selective-Catalytic Reduction	To any AGE exhaust	3
Water-in-Fuel Firing	To any AGE fuel	3
NOx-Filter Cart	To any AGE exhaust	3

NTD, SCR, and NFC were each awarded maximum points (3) because, as post-combustion NOx-control technologies, they are combustor independent.

WFF was also awarded maximum (3) points, because it is applicable to either diesel or jet fuel. Moreover, WFF was demonstrated on both fuels during these proof-of-concept tests.

DFF and OEA were each awarded 1 point, because each is specific to diesel engines, whereas other aerospace ground equipment includes gas-turbine combustors [2].

4.4.2 -86 Modification

The next element was "-86 Modification", a measure of the extent to which a working -86, as now configured, would need to be altered to achieve an emissions reduction.

Maximum points (3) were awarded to those technologies that could be deployed with no change in the -86. Lower scores (2 or 1) were earned as more changes were required. Zero points were earned if major, or irreversible, changes were required to implement NOx control.

Table 4.4.2 lists the assessment of -86 Modification, along with the scoring.

TABLE 4.4.2 -86 MODIFICATION

Green AGE Technology	-86 Modification	Points Scored Out of 3
Dual-Fuel Firing	Install gas injectors; retard timing	2
Non-Thermal Discharge	None	3
Oxygen-Enriched Air	Retard timing; install EGR	2
Selective-Catalytic Reduction	None	3
Water-in-Fuel Firing	Install larger injectors	2
NOx-Filter Cart	None	3

NTD, SCR, and NFC were each awarded maximum (3) points, because, as post-combustion technologies, no changes were required to the -86 for NOx reduction to be implemented. Current and "green" -86s would be operated the same.

DFF, OEA, and WFF were each awarded 2 points, because minor modifications to the -86 are necessary to implement the respective NOx-control technologies. For DFF, adjustments must be made to retard engine timing (RET), and to mount natural-gas injectors into the air intake manifold. For OEA, RET must also be performed, as well as the connection of -86 exhaust with air intake. For WFF, the normal-sized fuel injectors (N-65) must be replaced with larger-sized ones (N-90).

4.4.3 Weight, Volume, Footprint

This element assessed how the "Weight, Volume, Footprint" of a -86 would change if it were made "green" by equipping it with a working emissions-reduction technology.

If these characteristics did not change significantly, maximum points (2) were awarded. If some increase were required, 1 point was awarded. The NOx-reduction technology requiring the largest increase in weight, volume, and/or footprint of a -86 was awarded 0 points.

Table 4.4.3 lists the assessment of Weight, Volume, Footprint, along with the scoring.

TABLE 4.4.3 WEIGHT, VOLUME, FOOTPRINT

Green AGE Technology	Weight, Volume, Footprint	Points Scored Out of 2
Dual-Fuel Firing	Compressed natural gas supply	1
Non-Thermal Discharge	Filter, reactor, heat exchanger, wet scrubber	1
Oxygen-Enriched Air	MSOGS, EGR system	1
Selective-Catalytic Reduction	Filter, catalyst, ammonia supply	1
Water-in-Fuel Firing	Water supply, mixing tank	2
NOx-Filter Cart	Filter, heat exchanger, sorbent	1

WFF was awarded maximum (2) points, because it has the least "physical presence" of all the NOx-reduction technologies. The water supply need only consist of a delivery line. The mixing tank for preparing the emulsion could consist of a current one, appropriately modified.

DFF, NTD, OEA, SCR, and NFC were each awarded 1 point, because their physical presences with the NOx-reduction technology in operation will definitely be different. For DFF, a storage facility for compressed natural gas will need to be present, either on the -86, or nearby. For NTD, a "cart", about equal in weight, volume, and footprint to a -86, will be necessary. For OEA, the MSOGS would constitute a second piece of equipment to the flight line. For SCR, the main change in physical presence would be to add a storage system for the required ammonia, which could be in either compressed or dissolved (aqueous) form, either on the -86, or nearby. For NFC, a "cart", about equal in volume and footprint to a -86, will be necessary.

4.4.4 Revertibility

"Revertibility" assessed the degree of difficulty required to "decouple" an emissions-reduction technology from a -86, for rapid deployment to a location where emissions compliance was unneeded.

Points were awarded on the basis of this reversibility being "easy" (3), "moderate" (1), or "difficult" (0 points).

Table 4.4.4 lists the assessment of Revertibility, along with the scoring.

TABLE 4.4.4 REVERTIBILITY

Green AGE Technology	Revertibility	Points Scored Out of 3
Dual-Fuel Firing	Disconnect natural gas	3
Non-Thermal Discharge	Disconnect NTD cart	3
Oxygen-Enriched Air	Disconnect EGR, MSOGS systems	3
Selective-Catalytic Reduction	Disconnect SCR-stack system	3
Water-in-Fuel Firing	Reinstall fuel injectors	1
NOx-Filter Cart	Disconnect sorbent-filter cart	3

DFF, NTD, OEA, SCR, and NFC are inherently structured such that they can be readily decoupled from a -86 for its rapid deployment to a region where NOx control is not a necessity.

For WFF, switching from diesel-fuel/water or jet-fuel/water emulsions to the neat fuel requires the larger nozzles (N-90) for the emulsions be replaced with the original ones (N-65), if a ~30% engine derating is to be avoided. The time required to re-nozzle will depend upon the skill level of the flight engineer.

4.4.5 Supportability

"Supportability" assessed the extent to which ancillary, external services were required by each emissions-reduction technology to operate.

Those technologies requiring no external services, other than those currently needed by a -86, earned maximum (2) points. Those with intermediate needs earned 1 point. Those requiring multiple services earned 0 points.

Table 4.4.5 lists the assessment of Supportability, along with the scoring.

TABLE 4.4.5 SUPPORTABILITY

Green AGE Technology	Supportability	Points Scored Out of 2
Dual-Fuel Firing	On-line electricity, compressed natural gas	1
Non-Thermal Discharge	On-line electricity, ethanol, water	1
Oxygen-Enriched Air	On-line MSOGS or turbocharger	1
Selective-Catalytic Reduction	On-line ammonia, electric heater	1
Water-in-Fuel Firing	None	2
NOx-Filter Cart	On-line electricity	1

WFF scored maximum (2) points, because the emulsion could be delivered through existing fuel lines. In other words, a "green" -86 using WFF would require no additional support to operate.

DFF, NTD, OEA, SCR, and NFC each require external services to operate, ranging from electricity (DFF, NTD, OEA, NFC), to compressed natural gas (DFF), to chemicals (NTD, SCR). Each of these candidate Green AGE technologies therefore scored 1 point.

4.4.6 Fuel Compatibility

"Fuel Compatibility" assessed the fuel dependence of each emissions-reduction technology. Most -86s are fired with diesel fuel (DF2), whereas in the future, the fuel of choice is jet fuel (JP8).

Technologies that were fuel-independent (interchangeable between diesel and jet fuel) earned maximum points (3). Those technologies that could be switched from diesel to jet fuel with only minor adjustments earned 2 points. Those technologies that could switch from diesel to jet fuel with major adjustments earned 1 point. Technologies that were specific to diesel fuel earned 0 points.

Table 4.4.6 lists the assessment of Fuel Compatibility, along with the scoring.

TABLE 4.4.6 FUEL COMPATIBILITY

Green AGE Technology	Fuel Compatibility	Points Scored Out of 3
Dual-Fuel Firing	New injection rates, timing	2
Non-Thermal Discharge	Fuel independent	3
Oxygen-Enriched Air	Fuel independent	3
Selective-Catalytic Reduction	Fuel independent	3
Water-in-Fuel Firing	Fuel independent	3
NOx-Filter Cart	Fuel independent	3

Because NTD, SCR, and NFC are post-combustion NOx-control technologies, their performance is independent of the fuel fired, if emissions from the fuels fired are similar. Because NOx emissions from diesel-fuel firing are similar to those from jet-fuel firing [(5)], these technologies were considered fuel independent, and therefore scored maximum points (3). During the proof-of-concept demonstration, NTD was tested on JP8.

WFF also earned maximum (3) points, because the surfactant package used for diesel-fuel emulsions was interchangeable with that for jet-fuel emulsions. WFF was demonstrated on both diesel and jet fuel, with the performance somewhat "better" on jet fuel than diesel fuel [(23)].

For DFF to perform on jet fuel rather than diesel fuel, minor adjustments would be necessary to the natural-gas injection rate and timing. For this reason, DFF scored only 2 points.

4.4.7 Effect of Climate

"Effect of Climate" is a critical measure of deployability. This element assessed the effectiveness of an emissions-control technology to operate under different weather conditions. Conditions envisioned to influence effectiveness include temperature, relative humidity, and altitude.

Emissions-reduction technologies insensitive to climate earned maximum points (2). Those technologies that would be influenced by climatic conditions earned 0 points.

Table 4.4.7 lists the assessment of Effect of Climate, along with the scoring.

TABLE 4.4.7 EFFECT OF CLIMATE

Green AGE Technology	Effect of Climate	Points Scored Out of 2
Dual-Fuel Firing	Altitude dependent	1
Non-Thermal Discharge	Temperature dependent	1
Oxygen-Enriched Air	Altitude dependent	1
Selective-Catalytic Reduction	Temperature dependent	1
Water-in-Fuel Firing	Temperature dependent	0
NOx-Filter Cart	Temperature dependent	1

Each candidate technology is suspected of having some dependence on climate. Normal -86 operation is inherently influenced by climate, namely altitude (derated firing rates), and temperature (cold-start) conditions. NOx emissions are reduced ($\sim 5\%$) as relative humidity increases [10].

DFF, NTD, OEA, SCR, and NFC each scored 1 point, because climate was thought to have a minor, but correctable, effect. For DFF, natural-gas cofiring rates might have to be adjusted to correspond to corrections in liquid-fuel rate for altitude. For OEA, EGR might also have to be adjusted to correct for altitude effects. For NTD and NFC, adjustments might have to be made to their heat exchangers to accommodate for colder temperatures. For SCR, adjustments might be needed to the heater to keep the catalyst bed at temperature in cold climates, in-between -86 use.

WFF scored 0 points, because it has the greatest difficulty accommodating climatic changes. Possible problems include cold starting of the -86, and freezing of the fuel/water in the supply lines. These problems are correctable if a heater accompanied the -86 and its fuel-supply lines.

Overall, problems resulting from cold conditions are not insurmountable, if the deployment of the "green" -86s is at March AFB, CA. If deployment is at colder locations, the effect of climate could be as much a "show stopper" as achieving the minimum-NOx reduction.

4.4.8 Controllability

The last element of Deployability was "Controllability", which assessed how a flight engineer would "handle" a low-emissions -86, compared to a current one.

Two points were awarded to those emissions-reduction technologies that required no more involvement by a flight-engineer for the operation of a "green" -86 than for a current one. One point was awarded if the emissions-control technology required additional involvement. Zero points were awarded if more attention were required for the NOx-control technology than for the -86.

Table 4.4.8 lists the assessment of Controllability, along with the scoring.

TABLE 4.4.8 CONTROLLABILITY

Green AGE Technology	Controllability	Points Scored Out of 2
Dual-Fuel Firing	No more involvement	2
Non-Thermal Discharge	Major involvement	0
Oxygen-Enriched Air	Minor involvement	1
Selective-Catalytic Reduction	Minor involvement	1
Water-in-Fuel Firing	No more involvement	2
NOx-Filter Cart	Minor involvement	1

DFF and WFF each scored maximum (2) points, because each can be operated unattended. Integral to DFF technology is an electronic unit, which controls -86 and DFF operation. Once equipped with larger fuel nozzles for WFF, a -86 operates as it does firing neat diesel or jet fuel.

OEA, SCR, and NFC each scored 1 point, because they may not be operable unattended. For OEA, SCR, and NFC, a MSOGS, ammonia-injection, and pressure-monitoring system will have to be operated concurrently with the -86, respectively. Interfacing systems between these "add-on" devices and the -86 have not been designed or demonstrated.

NTD scored 0 points, primarily because of its system complexity, which involves the simultaneous use of a high-voltage reactor and transformer, ethanol-injector, and wet-scrubber.

4.4.9 Summary on Deployability

Table 4.4.9 lists the scoring of each candidate Green AGE technology in terms of the 8 elements of the Deployability criterion. As indicated, SCR and NFC tied for first, followed by a tie for second between NTD and WFF, and then a tie between DFF and OEA for last.

TABLE 4.4.9 DEPLOYABILITY RATING

Green AGE Technology	Points Scored (20 maximum)	Relative Ranking
Dual-Fuel Firing	13	3
Non-Thermal Discharge	15	2
Oxygen-Enriched Air	13	3
Selective-Catalytic Reduction	16	1
Water-in-Fuel Firing	15	2
NOx-Filter Cart	16	1

At the outset of the program, the 6 technologies were informally evaluated using the Rating System, and information provided by proponents and opponents. Scores ranged from 5 to 14 out of 20, with an average of 11. The span and distribution of these first-order scores indicated that the Rating System was sufficiently discriminating for evaluation purposes (see Appendix 1).

After the proof-of-concept demonstrations were completed, the same Rating System yielded the above scores, which ranged from 13 to 16 out of 20, with an average of 15. Without needing to reveal the details, the relative ranking of the 6 technologies changed somewhat since this first, informal evaluation. Hence, Phase II results had an impact on Deployability considerations.

To determine the variability in ratings for the Deployability criterion, each technology was scored by 3 different engineers. The variability in any total score was ± 1 point. This variability is enough to equalize the relative rankings of the 6 technologies. Hence, from a Deployability viewpoint, the six technologies considered are near-equal in terms of a relative ranking.

4.5 Fidelity of Data

The "Fidelity of Data" criterion was delineated by 3 elements. Each element related to the confidence that could be afforded the specific data used in the other rating criteria and elements.

4.5.1 Emissions Data

The first element, "Emissions Data", assessed whether the emissions-reductions data collected by each Green AGE technology proponent had been verified by independent measurements. In addition to this check, the reported data were compared to those published in the technical literature.

Direct verification of a proponent's emissions data earned maximum (4) points. Indirect verification earned 2 points. If these data could not be verified by any means, 0 points were earned.

Table 4.5.1 lists the assessment of Fidelity of Emissions Data, along with the scoring.

TABLE 4.5.1 FIDELITY OF EMISSIONS DATA

Green AGE Technology	Fidelity of Emissions Data	Points Scored Out of 4
Dual-Fuel Firing	Proponent data verified indirectly	2
Non-Thermal Discharge	Proponent data verified directly	4
Oxygen-Enriched Air	Proponent data verified indirectly	2
Selective-Catalytic Reduction	Proponent data verified directly	4
Water-in-Fuel Firing	Proponent data verified directly	4
NOx-Filter Cart	Proponent data verified directly	4

NOx reductions (Table 4.1.1) were checked on-site by an independent laboratory (see Appendix 2) [5]. All proponent-NOx data were either directly, or indirectly, validated independently.

Table 4.1.1 results were also compared with literature data. In DFF, a ~10% NOx reduction resulted from ~5° retarded engine timing (RET) [7], lower than that (40%) reported elsewhere [10]. In NTD, the 92% NOx reduction observed is the highest reported for NTD [13,14]. In OEA, NOx emissions increased, as observed before [17,18]. In OEA, ~5° RET caused a ~25% NOx reduction [16], lower than that (40%) reported elsewhere [10]. The ~50% NOx reduction for OEA was achieved using 10% EGR, comparable to that reported [10]. In SCR, the 96% reduction is higher than that (~80%) reported elsewhere [19,20]. In WFF, the 85-95% reduction observed is higher than that (50-70%) reported elsewhere [10,22]. In NFC, the ~90% reduction is a first-of-its-kind observation [24].

4.5.2 R&M Data

This element assessed the basis for the R&M data available on each candidate technology.

Maximum points (3) were awarded if the basis for R&M data were direct experience, that is, history on a deployed commercial product using the emissions-reduction technology. One point was earned if the basis were a combination of direct and indirect experience, involving both commercial components and prototypes. Zero points were earned if the basis were solely the extrapolation of proof-of-concept experience on prototypes only, tested under laboratory conditions..

Table 4.5.2 lists the assessment of Fidelity of R&M Data, along with the scoring.

TABLE 4.5.2 FIDELITY OF R&M DATA

Green AGE Technology	Fidelity of R&M Data	Points Scored Out of 3
Dual-Fuel Firing	Commercial	3
Non-Thermal Discharge	Prototype and commercial	1
Oxygen-Enriched Air	Prototype and commercial	1
Selective-Catalytic Reduction	Commercial	3
Water-in-Fuel Firing	Commercial	3
NOx-Filter Cart	Prototype and commercial	1

DFF, SCR, and WFF each scored maximum (3) points, because actual products based on these emissions-control technologies have been put into practice commercially.

NTD, OEA, and NFC each scored 1 point, because they represent a mix of commercial and prototype equipment. For NTD, the major component, the reactor, is a laboratory prototype, which will be used with a particulate filter, heat exchanger, and scrubber, all of which are commercial products. For OEA, although the MSOGS and accompanying technologies, RET and EGR, are "commercial", these processes were not tested together in the proof-of-concept demonstration. For NFC, although the sorbent (activated charcoal), particulate filter, and heat exchanger are commercial products, their assembly represents a prototype, which has had limited field testing.

4.5.3 Cost Data

This element assessed basis for the Cost data available on each candidate technology.

Maximum points (3) were awarded if the basis for cost data were direct experience, that is, the production and observation of a commercial product using the emissions-reduction technology. One point was earned if the basis were a combination of direct and indirect experience, involving both commercial components and prototypes. Zero points were earned if the basis were solely the extrapolation of proof-of-concept, laboratory experience.

Table 4.5.3 lists the assessment of Fidelity of Cost Data, along with the scoring.

TABLE 4.5.3 FIDELITY OF COST DATA

Green AGE Technology	Fidelity of Cost Data	Points Scored Out of 3
Dual-Fuel Firing	Product sold and in use	3
Non-Thermal Discharge	No product sold or in use	1
Oxygen-Enriched Air	No product sold or in use	1
Selective-Catalytic Reduction	Product sold and in use	3
Water-in-Fuel Firing	Product sold and in use by others	3
NOx-Filter Cart	No product sold	1

DFF, SCR, and WFF each scored maximum (3) points, because products based on these emissions-control technologies are sold commercially. For DFF and SCR, the proponents, BKM and HIS, respectively, each have products on the market. For WFF, the proponent, WL/FIVC, is a military establishment. However, systems utilizing WFF technology are sold commercially [10].

NTD, OEA, and NFC each scored 1 point. For NTD, the major component, the reactor, is a prototype, the components of which have not been finalized, causing NTD costs to be speculative. Costs for ancillary components of the NTD (particulate filter, heat exchanger, and wet scrubber) are reliable, because all are commercial products. For OEA, the costs for building and operating a MSOGS are known, as are those for accompanying technologies (RET and EGR). However, these elements were never tested together in the proof-of-concept demonstration, which would allow the cost of the technology to be more reliable. For NFC, although the sorbent (activated charcoal), particulate filter, and heat exchanger are commercial products, their assembly represents a prototype, which has had insufficient field testing to establish the costs with any reliability.

4.5.4 Summary on Fidelity of Data

Table 4.5.4 lists the scoring of each candidate Green AGE technology in terms of the 3 elements of the Fidelity of Data criterion. As indicated, SCR and WFF tied for first, followed DFF in second, NTD and NFC tied for third, and OEA in last place.

TABLE 4.5.4 FIDELITY OF DATA RATING

Green AGE Technology	Points Scored (10 maximum)	Relative Ranking
Dual-Fuel Firing	8	2
Non-Thermal Discharge	6	3
Oxygen-Enriched Air	4	4
Selective Catalytic Reduction	10	1
Water-in-Fuel Firing	10	1
NOx-Filter Cart	6	3

At the outset of the program, the 6 technologies were informally evaluated using the Rating System, and information provided by proponents and opponents. Scores ranged from 6 to 10 out of 10, with an average of 8. The span and distribution of these first-order scores indicated that the Rating System was sufficiently discriminating for evaluation purposes (see Appendix 1).

After the proof-of-concept demonstrations, the same Rating System yielded almost the same scores, and exactly the same relative ranking.

To determine the variability in ratings for the Fidelity of Data criterion, each technology was scored by 3 different engineers. The variability in any total score was ± 1 point. This variability is not enough to alter the relative rankings of the 6 technologies, which can be viewed, from a Fidelity of Data viewpoint, as consisting of 2 groupings: SCR, WFF, and DFF in a first one, and NTD, NFC, and OEA in a second one.

5.0 OVERALL RANKINGS AND ANALYSIS

Table 5.1 lists the scores. Based on these results, the 6 candidate NOx-reduction technologies considered in Green AGE Phase II can be ranked in the following order of decreasing merit:

1. **Water-in-Fuel Firing (WFF), WL/FIVC, Tyndall AFB, FL;**
2. **Selective-Catalytic Reduction (SCR), Houston Industrial Silencing, TX;**
3. **NOx-Filter Cart (NFC), AL/EQ, Tyndall AFB, FL;**
4. **Oxygen-Enriched Air (OEA), AL/CFTS, Brooks AFB, TX;**
5. **Dual-Fuel Firing (DFF), BKM, San Diego, CA; and**
6. **Non-Thermal Discharge (NTD), WL/MNMW, Eglin AFB, FL.**

Because the cumulative uncertainty in the analysis was ± 5 points, the difference between the No. 1 and 2-rated technologies (WFF: 76 points; SCR: 68 points, respectively) is just discriminating. The difference between the No. 2 and 3-rated technologies (SCR: 68 points; NFC: 60 points) is not. The difference between these top-3 technologies and the others (OEA, DFF, NTD) is discriminating.

An analysis was conducted to determine what would be required for this ranking to change. Analyzed first was whether the top-3 and bottom-3 technologies could ever reverse rankings.

Consider the following. First, NTD is the least developed and proven, and most complex and costly technology of the 6 considered. Second, DFF and OEA failed to achieve the 70%-minimum NOx reduction, despite also using retarded engine timing (RET) and exhaust gas recirculation (EGR). Because the time to implement Green AGE is short, and technical experience indicates that a $\leq 50\%$ NOx reduction is the best that DFF, RET, and EGR can ever achieve, NTD, DFF, and OEA cannot be expected to surpass WFF, SCR, or NFC, unless a major technical breakthrough occurs [10,19,20].

The ranking of the top-3 technologies (WFF, SCR, NFC) appears somewhat interchangeable. For SCR to overtake WFF, acceptable NOx reductions ($>70\%$) must be demonstrated at low loads. This could be accomplished by elevating the temperature of the SCR catalyst using a heater, a component that might also be required by DFF to keep emulsions from freezing in cold climates. Hence, adding a heater to both technologies could eliminate respective deficiencies.

For NFC to surpass WFF or SCR, uncertainties regarding the capacity and cost of the sorbent must be resolved. Given the promise of NFC, these questions should be pursued in Phase III.

In summary, on an emissions-reduction, cost, reliability, maintainability, deployability, and fidelity basis, WFF, SCR, and NFC have more technical merit and timeliness as candidate technologies for the Green AGE Initiative than do OEA, DFF, and NTD.

TABLE 5.1 NUMERICAL RATINGS OF GREEN AGE TECHNOLOGIES

RATING ELEMENT/TECHNOLOGY	DFF	NTD	OEA	SCR	WFF	NFC
NOx Reduction	0	6	0	5	10	8
Impact on CO	0	1	2	3	1	3
Impact on ROx	3	1	3	1	3	1
Impact on RHC	0	2	3	2	0	3
Secondary Emissions	2	2	2	1	3	3
Deployment Schedule	3	0	1	3	3	2
TOTAL: EMISSIONS REDUCTION (25)	**8**	**12**	**11**	**15**	**20**	**20**
Capital Costs	1	0	5	2	10	1
Operating Costs	5	1	9	15	5	5
TOTAL: COST (25)	**6**	**1**	**14**	**17**	**15**	**6**
Reliability	0	1	1	0	2	1
Maintainability of -86	1	2	1	2	1	2
Maintainability of Technology	2	0	1	1	1	0
Functionality	1	0	0	1	2	1
Availability of Supplies	2	0	1	0	1	1
Feasibility	2	0	2	2	2	2
Safety of -86 Operation	2	1	2	2	4	3
Life-Cycle of Materials	2	1	1	1	2	1
Training	1	0	1	1	1	1
TOTAL: R & M (20)	**13**	**5**	**10**	**10**	**16**	**12**
Applicability	1	3	1	3	3	3
-86 Modification	2	3	2	3	2	3
Weight, Volume, Footprint	1	1	1	1	2	1
Revertibility	3	3	3	3	1	3
Supportability	1	1	1	1	2	1
Fuel Compatibility	2	3	3	3	3	3
Effect of Climate	1	1	1	1	0	1
Controllability	2	0	1	1	2	1
TOTAL: DEPLOYABILITY (20)	**13**	**15**	**13**	**16**	**15**	**16**
Fidelity: Emissions Data	2	4	2	4	4	4
Fidelity: R&M Data	3	1	1	3	3	1
Fidelity: Cost Data	3	1	1	3	3	1
TOTAL: FIDELITY OF DATA (10)	**8**	**6**	**4**	**10**	**10**	**6**
TOTAL SCORE: (100)	**48**	**39**	**52**	**68**	**76**	**60**

6.0 CONCLUSIONS AND RECOMMENDATIONS

Based on Phase II of the Green AGE Initiative, the following were concluded:

- Water-in-Fuel Firing (WFF), Selective-Catalytic Reduction (SCR), and NOx-Filter Cart (NFC) have merit as technologies with which to bring aerospace ground equipment (AGE) at March AFB, CA, into peace-time environmental compliance.

- Although they have merit as emissions-reduction technologies, WFF, SCR, and NFC are not turnkey solutions to the March AFB problem, and, therefore, are recommended for continued development and demonstration under Phase III of the Green AGE Initiative.

- Because it is available, commercial experience in the use of WFF and SCR, by vendors other than the proponents who demonstrated these technologies in Phase II, should be taken advantage of in Phase III demonstrations.

- Compared to WFF, SCR, and NFC, Dual-Fuel Firing, DFF, Oxygen-Enriched Air, OEA, and Non-Thermal Discharge, NTD have deficiencies, the resolution of which is doubtful within the time (NTD) a Green AGE technology is needed at March AFB, or doubtful technically at all (DFF and OEA), and are not recommended for demonstrations under Phase III of the Green AGE Initiative.

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APPENDIX 1:

TEST PLAN AND RATING SYSTEM FOR GREEN AGE PHASE II

March 1996

TEST PLAN AND RATING SYSTEM

for

EVALUATION OF AIR EMISSIONS-REDUCTION TECHNOLOGIES FOR AEROSPACE GROUND EQUIPMENT
Phase II: Green AGE Initiative)

(Unclassified)

Prepared for

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Contract No. F33657-92-D-2055
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March 1996

TEST PLAN AND RATING SYSTEM
for
EVALUATION OF AIR EMISSIONS-REDUCTION TECHNOLOGIES
FOR AEROSPACE GROUND EQUIPMENT
to
AL/HRGO
Wright-Patterson AFB OH

1.0 INTRODUCTION

This document provides information on the conduct of Phase II of a United States Air Force (USAF) initiative to reduce air emissions from diesel-powered aerospace ground equipment (AGE) at March Air Force Base (AFB), California. The project is referred to as the "Green AGE" Initiative.

2.0 PROJECT BACKGROUND

Reauthorization of the Clean Air Act by the US Environmental Protection Agency (EPA) has levied air-quality standards on the USAF [1]. After determining that aerospace ground equipment at March AFB could not meet the current standards for nitrogen-oxides (NOx) emissions set forth by the South Coast Air Quality Management District (SCAQMD), the USAF established a team to identify, develop, demonstrate, and implement hardware solutions to this air emissions problem [2].

As required to ensure that USAF systems are capable of meeting peacetime requirements, the Logistics Research Division (HRG) of the Operational Logistics Branch of Armstrong Laboratory (AL/HRGO) solicited military and civilian laboratories to identify current technologies that could bring March AFB into compliance. In Phase I, five candidates technologies were identified as having the most promise with regard to solving the March AFB problem [2]. In Phase II, these 5 candidates are to be demonstrated by their proponents on actual Green AGE equipment. Battelle has been contracted as the "honest broker" in Green AGE Phase II, and given the task of designing a Test Plan for the demonstrations, and formulating a Rating System for the evaluation, which may ultimately lead to one emission-reduction technology being deployed in a Phase III effort on Green AGE.

3.0 SCOPE

The technology scope involves 5 different approaches to NOx-emissions reduction, as follows [1,2]:

- Dual-Fuel Firing (DFF),
- Non-Thermal Discharge (NTD),
- Oxygen-Enriched Air (OEA),
- Selective-Catalytic Reduction (SCR), and
- Water-in-Fuel Firing (WFF).

Three of the technologies involve pre-combustion intervention, to prevent NOx formation. In DFF, diesel fuel is cofired with natural gas. In OEA, the oxygen content of the combustion air is increased to above 21%. In WFF, water is emulsified with the diesel fuel. The 2 remaining technologies involve the post-combustion removal of NOx. In NTD and SCR, the removal process involves the use of ammonia and an electrical field or catalyst, respectively, to reduce NOx to nitrogen dioxide (NO_2) or nitrogen acids (HNO_y). Upon each reduction in NOx, the goal also is to not increase the emission of carbon monoxide (CO), particulates (ROx), or reactive hydrocarbon emissions (RHC).

4.0 OBJECTIVE OF BATTELLE AS "HONEST BROKER'

Battelle's objective as "honest broker" is to perform an independent evaluation of the engineering feasibility of the 5 candidate emissions-control technologies. To do so, a Test Plan for conducting the proof-of-concept demonstrations, and a Rating System for evaluating the results, have been drafted. To the extent possible, the Test Plan and Rating System are comprehensive, discriminating, objective, rigorous, and fair. The approach used to draft the Test Plan and Rating System is discussed next.

5.0 APPROACH

The Test Plan and Rating System should provide the methodology and details on what is needed to be done and known, with certainty, to establish base lines and targets, identify promise and problems, monitor progress, and at program completion, objectively identify the most acceptable technology, from a March AFB perspective.

The Test Plan was designed to adopt, by default, protocols like those used by the state (SCAQMD) [3] and federal (EPA) [4] agencies, which sanction emissions-reduction technology before it is deployed. Moreover, in Green AGE Phase I, data were acquired to establish a baseline for AGE emissions, whose test protocol satisfied the general requirements imposed by the EPA and SCAQMD.

The approach taken to define a Rating System was to elaborate upon the "Exit Criteria" developed by AL/HRC in Phase I to select the 5 best emissions-reduction technologies from the 11 submitted [1,2]. More exacting specifics for each rating criterion were identified. All criteria specific to any one technology were first identified, and then, quantified (most-to-least promising/problematic scale). The Rating System was tested, using existing information, to determine if it were discriminating.

The Test Plan and Rating System will be reviewed by AL/HRGO and candidate contractors before implementing. Each candidate will have the opportunity to confirm that it could satisfy the requirements of the Test Plan, and to suggest which criteria should, or should not, be included in the final Rating System, and the relative numerical importance given each. Battelle will then compile this information, and be the independent judge in finalizing the Test Plan and Rating System.

During Phase II, each contractor should self-evaluate its technology using the Rating System, for information purposes only. These preliminary data will establish the status of each technology, and monitor progress. Such an effort is necessary because much essential information was missing, incomplete, or estimated in the proposals that qualified the Technologies in Phase I [1].

Each candidate will have opportunities throughout the demonstration period to provide additional, more complete, and/or definitive data for Battelle to consider. At the conclusion of the demonstration period, each candidate will submit its best information for use in the final evaluation by Battelle. In this last evaluation, information from the candidates will be compared with that available in the technical literature on NO_x-control, on which Battelle has compiled a data base.

This approach will ensure that all and the best information is used in the final analysis, upon which a "Go/No Go" decision for Phase III implementation by the USAF will be based.

6.0 ELEMENTS OF THE TEST PLAN

Each technology is to be demonstrated on a diesel-fueled A/M32A-86 ("-86") electrical generator, supplied to them by the USAF. The following series of outlines provides essential information on how testing for demonstration will be conducted.

6.1 Protocols

Baseline emissions will be determined on a properly tuned -86 before any modifications are made.
Baseline-emissions measurements will be conducted in-house using EPA/SCAQMD-like protocols.
Controlled-emissions measurements will be conducted in-house with EPA/SCAQMD-like protocols.
Final-emissions measurements will be conducted in-house using EPA/SCAQMD-like protocols.
Final emissions data will be subject to independent confirmation by an outside testing laboratory.
Final, independent-emissions measurements will be conducted using EPA/SCAQMD-like protocols.

A manual on EPA/SCAQMD emission-measurement protocols accompanies this document.

6.2 Data Required

Baseline measurements will be done in triplicate on 2 different days at 3 different amp-loadings.
Final measurements will be done in triplicate on 2 different days at 3 different amp-loadings.
Primary emissions to be measured are NOx, CO, ROx, RHC, carbon dioxide (CO_2) and oxygen (O_2).
Secondary emissions to be measured are methane (CH_4), ammonia (NH_3), and ozone (O_3).
Ancillary data includes diesel-fuel consumption, and exhaust-gas flow rate and temperature.
Meteorological data to be recorded include ambient air temperature and relative humidity.

6.3 Documentation

Information to be provided include details on the -86 generator:

Initial status, and modifications made to the engine and/or exhaust system,
Problems experienced with engine operation, and corrective actions taken,
Routine maintenance and servicing performed,
Total hours of use, with and without the emissions-reduction technology in place, and
Fuel source, specifications, and quality,

Additional information to be provided includes details on the emissions-measurement protocols:

Sampling position, sampling probe and train dimensions, construction, and operation,
Instrumental analyzers, models, and scale ranges used,
Calibration gases, concentrations used, and
Instrument calibration criteria.

Should modifications to the Test Plan be required, all candidates will be informed accordingly.

6.4 Reporting

Information required by this Test Plan should be simultaneously communicated to AL/HRGO and Battelle for compilation and analysis. A standard form is being contemplated to assist in this reporting. More information on reporting will follow, after some technical progress has been made.

7.0 ELEMENTS OF THE RATING SYSTEM

The Rating System consists of 5 "Rating Criteria", listed in Table 1. Each has been weighted in terms of "Relative Importance", defining a 100-point scoring system. "Emissions Reduction" and "Cost" were given equal and the highest importance, followed by "Reliability and Maintainability" and "Deployability", given a lower (equal) importance. These rankings were based on experience with another USAF multi-attribute analysis [6]. "Fidelity of Data" assess confidence in the data.

TABLE 1. RATING CRITERIA AND RELATIVE IMPORTANCE

RATING CRITERIA	RELATIVE IMPORTANCE
Emissions Reductions	25%
Cost	25%
Reliability and Maintainability	20%
Deployability	20%
Fidelity of Data	10%

Table 2 lists how each of the 5 Rating Criteria was internally specified, and the point values to be awarded within each in terms of 28 components. Each criteria/component is discussed next.

7.1 Emissions Reduction

The "Emissions Reductions" criterion was delineated by 6 components. Because it constitutes the prime objective, "NOx Reduction" was given the highest value of any single component (10 points). Points are scored based on the extent of the NOx reduction achieved. Technologies achieving >90% reduction earn maximum points, followed by those achieving reductions in the 80% (8 points) and 70% ranges (5 points). Technologies achieving <69% NOx reduction scored 0 points.

The next 3 components involve the impact of the NOx reduction on the other criteria pollutants: CO, ROx, and RHC, each of which are "in SCAQMD compliance" at March AFB [2]. Points are awarded on the basis of how the NOx-control technology effects these other emissions. Maximum scores (3 points) are awarded if the NOx-control technology reduces these pollutants; 0 points are awarded if the NOx-reduction results in an increase in CO, ROx, and/or RHC. 1 point is awarded if the NOx-reduction has no effect on these other emissions.

The next component describes whether the use of a NOx-reduction technology causes the emission of a new, or "secondary", pollutant. From a review of the candidate technologies, the secondary emission of CH_4, NH_3, O_3, or O_2 are possible. Maximum points (3) are given if such secondary emission does not take place. Zero points are given if any secondary pollutant/hazard is emitted.

The last component assesses when the NOx reduction can be deployed, with target dates given by SCAQMD [1,2]. Deployment by 1997 earns maximum points (3); deployment by 1999 earns 1 point. To determine whether this scoring system was sufficiently discriminating, the 5 technologies were informally evaluated using information either claimed by proponents/opponents, or from the literature. Scores ranged from 4/25 to 19/25, with an average of 13/25. The distribution of these first-order scores indicates that the scoring system is sufficiently discriminating for evaluation purposes.

TABLE 2. RATING CRITERIA AND RATING SYSTEM

EMISSIONS REDUCTIONS: 25 POINTS	NOx REDUCTION	>90%	10
		80-89%	8
		70-79%	5
		<69% (disqualified)	0
	IMPACT ON CO	DECREASE	3
		REMAINS THE SAME	1
		INCREASE	0
	IMPACT ON ROx	DECREASE	3
		REMAINS THE SAME	1
		INCREASE	0
	IMPACT ON RHC	DECREASE	3
		REMAINS THE SAME	1
		INCREASE	0
	SECONDARY EMISSIONS	NONE	3
		ANY	0
	DEPLOYMENT SCHEDULE	BY 1997	3
		BY 1999	1
COST: 25 POINTS	CAPITAL	LOWEST	10
		HIGHEST	0
	LIFE CYCLE	LOWEST	15
		HIGHEST	0
RELIABILITY & MAINTAINABILITY: 20 POINTS	RELIABILITY	ON -86 DEMAND	2
		NOT ON -86 DEMAND	0
	MAINTAINABILITY OF -86	LESS SERVICE HOURS	2
		SAME SERVICE HOURS	1
		MORE SERVICE HOURS	0
	MAINTAINABILITY OF TECHNOLOGY	LEAST SERVICE HOURS	2
		MOST SERVICE HOURS	0
	FUNCTIONALITY	NO MORE POWER REQUIRED	2
		ADDED POWER REQUIRED	0
	AVAILABILITY OF SUPPLIES	OFF THE SHELF	2
		NOT OFF THE SHELF	0
	FEASIBILITY	DEMONSTRATED ON -86	2
		NOT DEMONSTRATED ON -86	0
	SAFETY OF -86 OPERATION	REMAINS THE SAME	4
		SOME NEW DANGER	2
		MANY NEW DANGERS	0
	LIFE-CYCLE OF MATERIALS	RECYCLABLE WASTES	2
		DISPOSAL PROBLEMS	0
	TRAINING	SAME AS FOR -86	2
		MINOR UPGRADE	1
		MAJOR RETRAINING	0
DEPLOYABILITY: 20 POINTS	APPLICABILITY	ALL/ANY AGE	3
		ONLY -86 AGE	1
	-86 MODIFICATION	NONE	3
		MINOR	1
		MAJOR	0
	WEIGHT/AREA/FOOTPRINT	EQUAL TO -86	2
		GREATER THAN -86	0
	REVERSIBILITY	EASY	3
		MODERATE	1
		DIFFICULT	0
	SUPPORTABILITY	NO ANCILLARY SYSTEMS	2
		ANCILLARY SYSTEMS	0
	JP-8 COMPATIBILITY	YES, WITHOUT ADJUSTMENT	3
		YES, BUT ADJUSTMENTS	2
		NOT NOW	0
	EFFECT OF CLIMATE	INSENSITIVE	2
		SENSITIVE	0
	CONTROLLABILITY	AS AN -86 SYSTEM	2
		AS ANOTHER SYSTEM	0
FIDELITY OF DATA: 10 POINTS	EMISSIONS DATA	VALIDATED	4
		NOT VALIDATED	0
	BASIS FOR R & M	UNITS IN SERVICE	3
		PROTOTYPE ONLY	1
	BASIS FOR COSTS	EXPERIENCE	3
		PROTOTYPE	1

7.2 Cost

The "Cost" criterion was delineated by 2 components, "Capital" and "Life-Cycle", given maximum point values of 10 and 15, respectively. The technology with the lowest cost in each category receives maximum points. The others are scored proportionately relative to the lowest cost, with the highest-cost technology receiving 0 points.

This scoring system was deemed sufficiently discriminating for use, because first-order estimates for non-recurring and recurring costs, based on data supplied by individual proponents, varied by about an order-of-magnitude (1/25 to 15/25) [1,2].

7.3 Reliability and Maintainability

The "Reliability and Maintainability" criterion was delineated by 9 components. Each of the components is of equal value (2 points), except for "Safety of -86 Operation" (4 points).

The "Reliability" component was defined as to whether the emissions-reduction afforded a technology is performed "on demand", that is, is "on" at cold start-up, and which follows load changes. Full points (2) are scored if the technology has maximum effectiveness "on-demand". No points are scored if the technology needs a delay time before it can reduce emissions to any extent >69%.

"Maintainability" was divided into 2 components, one for the -86 generator, and the other for the emissions-reduction technology. Maximum points (2) are awarded for the technology that results in a lower number of service hours for the -86, and which needs the least number of service hours itself. The technologies requiring more service maintenance than this receive 0 points.

"Functionality" describes the power needs of the emissions-reduction technology. Those requiring no more than the -86 surplus can provide receive 2 points; those requiring more power receive 0 points.

"Availability of Supplies" and "Feasibility" account for whether parts are off-the- shelf or custom, and whether demonstration was achieved on an -86, with 2 points each for being/having done so.

"Safety of -86 Operation" characterizes whether the normal operation of an -86 is made more dangerous with the use of an emissions-reduction technology. Risks such as those posed by use of high-voltages, and compressed oxygen, natural gas, and ammonia, are envisioned. Maximum points (4) are awarded if safety is not compromised by the operation of an emissions-reduction technology. Fewer points are given as new risks arise.

"Life-Cycle of Materials" assesses any added pollution potential an emissions-reduction technology may have. Technologies that recyclable materials or wastes earn maximum (2) points.

The last component accounts for "Training" the flight-line crew to operate an -86 generator with reduced emissions. The lower the number of additional training, the more points scored (up to 2).

To determine if the scoring system for "Reliability and Maintainability" was sufficiently discriminating, each of the 5 technologies was evaluated using available information. Scores ranged from 8/20 to 17/20, or a factor of 2 variation. The average was 13/20. Thus, the scoring system was deemed appropriate for evaluation.

7.4 Deployability

The "Deployability" criterion was delineated by 8 components, each with 2 or 3 maximum points.

The first measure, "Applicability", defines if an emissions-reduction technology were specific to the -86, or could be universally deployed on aerospace ground equipment. Maximum points (3) are given for being universally adaptable. One point is given if the technology is specific to the -86.

The next component was "-86 Modification", a measure of the extent to which a working -86, as now configured, would need to be altered to effect an emissions reduction. Maximum points (3) are given to those technologies that can be deployed with no changes in the -86. A lower score (1) is given if "minor" changes are required. Zero points are given if "major" changes are required.

The closer the "Weight/Area/Footprint of an -86 equipped with a working emissions-reduction technology are to the original -86, the more points (up to 2) are awarded.

"Reversibility" is a measure of the degree of difficultly required to "decouple" an emissions-reduction technology from an -86 for rapid deployment. Points are awarded on the basis of this "reversibility" being "easy" (3 points), "moderate" (1 point), or "difficult" (0 points).

"Supportability" is intended to characterize the ancillary systems required by the emissions-reduction technology. Those envisioned include additional storage tanks for natural gas, oxygen, ammonia, or water/surfactant. The technology with the least support equipment earns maximum (2) points.

"JP-8 Compatibility" assesses the future deployability of an emissions-reduction technology. Technologies that are fuel-independent earn maximum points (3). Those that may be able to accommodate diesel, as well as JP-8, fuel with minor adjustments, receive 2 points. Technologies that are specific to only diesel fuel earn 0 points.

The "Effect of Climate" is a critical measure of deployability. Climatic conditions that may influence the effectiveness of the candidate emissions-reduction technologies include altitude and relative humidity. Emissions-reduction technologies insensitive to climate earn maximum points (2). Those that may lose effectiveness because of climatic conditions receive 0 points.

The last measure of "Deployability" is "Controllability", or how a flight engineer will "handle" a low-emissions -86 compared to a current one. Points will be awarded to those emissions-reduction technologies that minimize flight engineer involvement in the operation of a "green" -86.

Again, to determine if the scoring system for "Deployability" was sufficiently discriminating, each of the 5 technologies was evaluated using available information. Scores ranged from 5/20 to 14/20. The average was 11/20. The scoring system was deemed appropriate for evaluation.

7.5 Fidelity of Data

The "Fidelity of Data" criterion was delineated by 3 components. Each relates to the confidence afforded the data used in the other rating criteria.

The first measure, "Emissions Data", accounts for whether the emissions reductions reported are verified by measurements by an independent laboratory. This component is intended to take into account variations in emissions data that may result from artifacts in the measurement protocols. Validation earns full points (4). Deviations can be viewed as points not awarded, or penalty points.
"Basis for R&M" and "Basis for Costs" are intended to address the sources of the data used to gather information for scoring purposes. Maximum points (3) are awarded for each if the bases for these estimates is experience from actually deployed technology. Minimal (1) points are awarded if the bases for the estimates are from the extrapolation of proof-of-concept or prototype data only.

Based on available estimates, and assuming all emissions data were verified, scores for this rating criterion ranged from 6/10 to 10/10, with an average of 8/10. Better discrimination may result upon using the results of actual emissions-reduction validation tests.

8.0 SUMMARY

A Test Plan/Rating System have been developed to assess demonstration-test results on the 5 candidate emissions-reduction technologies. Based on analysis of preliminary data, the Rating System is discriminating, as total scores range from 39 to 68 points. The next step is to recalculate these scores using more up-to-date, firm, and complete data on each technology from its proponent.

9.0 REFERENCES

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2. "Reducing Emissions from March AFB Aerospace Ground Equipment", Final Recommendation to SAF/AQT, Captain Douglas Furst, USAF, 20 June 1995.

3. "Emissions from Gaseous- and Liquid-Fueled Internal Combustion Engines", Rule 1110.2, South Coast Air Quality Management District, 7 September 1990.

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APPENDIX B:

SAMPLING AND TESTING OF EMISSIONS FROM FLIGHT-LINE DIESEL-POWERED ELECTRICAL GENERATORS

October 1996

Final Report

for

SAMPLING AND TESTING OF EMISSIONS FROM FLIGHT-LINE DIESEL-POWERED ELECTRICAL GENERATORS

(Unclassified)

Prepared for

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Army Research Office Contract No. DAAL03-91-C-0034/DO 1910
Task Control Number 96-138
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October 31, 1996

FINAL REPORT
for
SAMPLING AND TESTING OF EMISSIONS FROM FLIGHT-LINE DIESEL-POWERED ELECTRICAL GENERATORS
to
OC AL HSC/HRG
Wright-Patterson AFB, OH

October 31, 1996

1.0 INTRODUCTION

This document reports the results of one task on a United States Air Force (USAF) initiative to reduce air emissions from aerospace ground equipment (AGE) at March Air Force Base (AFB), CA. That project is referred to as the "Green AGE" Initiative.

2.0 BACKGROUND

Reauthorization of the Clean Air Act by the US Environmental Protection Agency (EPA) may levy air-quality standards on the USAF (1). After determining that aerospace ground equipment at March AFB could not meet the current standards for nitrogen-oxides (NO_x) emissions set forth by the South Coast Air Quality Management District (SCAQMD), the USAF established a team to identify, develop, demonstrate, and implement hardware solutions to this air-emissions problem (2).

To ensure that USAF systems are capable of meeting peacetime requirements, the Logistics Research Division of the Operational Logistics Branch of Armstrong Laboratory solicited military and civilian laboratories to identify current technologies that might bring March AFB into compliance.

In Phase I, candidate technologies were identified as having promise with regard to solving the March AFB problem (3). In Phase II, these emissions-control technologies were to be demonstrated by their proponents on actual Green AGE equipment, and then evaluated by an "Honest Broker" for technical merit. Promising technologies would be developed further in Phase III of Green AGE.

Battelle Columbus Operations (BCO) was selected by the USAF as the Honest Broker for Green AGE Phase II. One task in this capacity was to independently verify the emissions-reductions reportedly achieved by each technology. Validation of these data is the sole focus of this report.

Data provided here were used by Battelle in its Final Report on Green AGE Phase II: "Evaluation of Air Emissions-Reduction Technologies for Aerospace Ground Equipment", in which candidate technologies were evaluated for merit, and for development under Green AGE Phase III (4).

3.0 OBJECTIVE

The objective of this Green AGE Phase II task was to perform on-site measurements of emissions from an A/M32A-86 ("-86") electrical generator (72 kilowatts, 400 Hertz, 115 volts), with and without prototype emissions-reduction technologies in operation. The -86s were provided to each site by the USAF for the express purpose of demonstrating candidate Green AGE emissions reduction technologies. Battelle measurements were intended to verify that emissions data gathered by each technology proponent were valid, in accuracy and statistical terms, so that they could be used, with confidence, in the evaluation of technologies for the Green AGE Phase III competition [4].

4.0 APPROACH

The approach taken was for Battelle staff to collect data at each site where a particular emissions-reduction technology was being developed and proof-of-contest tested by a proponent. These field sampling trips took place over 1-3 day periods during July-September, 1996. When on site, the intent was to have the technology proponent's and Battelle staff make side-by-side measurements of specific emissions from the -86, without (baseline) and with the emissions-reduction technology in operation. Each proponent was allowed to "optimize" its technology before testing. Emissions measurements were performed in triplicate, using EPA and SCAQMD-recommended procedures [5], with the -86 generator operating at three different loads (amps): 0 (idle), 100, and 200. These loads were simulated using a load bank, also provided by the USAF to each site.

Because the goal was to validate data, the procedure had to be as standardized as possible. BCO measured emissions from -86 exhaust ports with an ENERAC 3000 Stack Emissions Analyzer (no endorsement implied). This commercial instrument was selected because it: 1) met EPA recommendations for continuous emissions-measuring devices [5-6]; 2) could simultaneously measure 3 of the 4 targeted emissions (NO_x, carbon monoxide, CO, and reactive hydrocarbons, RHC), as well as oxygen (O_2) and carbon dioxide (CO_2); 3) came equipped with a built-in probe and sample-transfer line, and 4) was portable and could be operated by one person, making it cost effective to use in a multi-site field testing program. Particulates were monitored using a Bacharach Model 21-7006 True Spot Smoke Tester (no endorsement is implied), recognized as an acceptable method for measuring semiquantitative and relative concentrations of particulates from combustion sources, notably diesel engines.

5.0 CANDIDATE EMISSION-REDUCTION TECHNOLOGIES

The 6 candidate NO_x-reduction technologies, their proponents, and locations, were as follows:

- Dual-Fuel Firing (DFF), BKM, San Diego, CA;
- Non-Thermal Discharge (NTD), WL/MNMW, Eglin AFB, FL;
- Oxygen-Enriched Air (OEA), AL/CFTS, Brooks AFB, TX;
- Selective Catalytic Reduction (SCR), Houston Industrial Silencing (HIS), Houston, TX;
- Water-in-Fuel Firing (WFF), WL/FIVC, Tyndall AFB, FL; and
- NO_x-Filter Cart (NFC), AL/EQ, Tyndall AFB, CA.

Half the technologies, DFF, OEA, and WFF, involved pre-combustion intervention, to prevent NO_x formation by the AGE. In DFF, generator fuel (diesel or JP8) was cofired with natural gas. In OEA, the oxygen content of the combustion air was increased to levels above 21%. In WFF, water was either sprayed into the cylinder or emulsified into the generator fuel.

The other 3 technologies, NTD, SCR, and NFC, involved post-combustion intervention, to remove unabated NO_x generated by an -86. In NTD and SCR, removal of NO_x from the -86 exhaust was an "active" process, involving the use of ammonia and an electrical field, respectively, to reduce NO to another component of NO_x, nitrogen dioxide (NO_2), which, in turn, was removed by wet scrubbing. In NFC, the removal process was passive, with the generated NO_x being removed by a sorbent filter.

Upon NO_x reduction, the accompanying goal was to not increase the emission of other criteria pollutants: CO, RO_x, and RHC, and to not effect the normal operation and/or performance of the -86.

The extent of emissions reduction achieved by each candidate technology was one element of a numerical rating system designed to down-select the 6 candidates for Green AGE Phase III [(4)]. Other elements of this rating system were cost, reliability, maintainability, deployability, and the fidelity of data. The last of these elements was what made this task necessary. Candidates would begin to score points if their technologies reduced NO_x by 70%, more points if the reduction in NO_x were >70%, and maximum points if the reduction were >90% and independently validated by BCO.

6.0 VALIDATION OF EMISSION-REDUCTION TECHNOLOGIES

Tables 1-6 contain the results of the independent testing by Battelle of the performance of the aforementioned emissions-reduction technologies, compared with data acquired by each proponent.

The format of each of these 6 tables is the same. The left-most column lists the laboratory performing the emissions measurement, either one of the technology proponents, or Battelle (BCO). The next column lists the fuel fired by the -86 generator. The test fuel was No. 2 diesel (DF2) in all but one case (WL/MNMW), where it was jet fuel (JP8). The third left-most column lists the load put on the -86 by a load bank: either 0 amps (idle), 100 amps, or 200 amps. The next column lists whether the emissions were measured with the -86 in its original status (baseline), or whether an emissions-control technology was in use (+ xxx).

The 6 right-most columns of Tables 1-6 list the emissions data. For completeness, O_2 and CO_2 were listed along with the pollutants of interest, NO_x, CO, RHC, and RO_x, as these "clean" exhaust gases provide information as to the general performance of the -86. Emissions data are listed either as an as-measured (am), percent (%), parts-per-million (ppm), or relative (spot no.) concentration. When data were not measured by either lab at any particular load, the entry is "not measured", (NM). If an emissions-reduction technology was not functional at any load, the entry is "not determinable" (ND). When a comparison between data from different labs was not possible for either or both these reasons, the entry is blank ("-").

The first 3 sets of 3 rows under each column heading compare the emissions data of a technology proponent with those of BCO under baseline conditions, first in terms of absolute concentration and then in relative terms (difference, in %). This sequence of rows is then repeated with an emissions-control technology in operation on the -86 for the same set of operating loads. The last 6 rows of each table contain the information of ultimate importance. That is, the extent to which an emissions-control technology changes the concentration of each specific criteria pollutant, and the extent to which this change, reported by a proponent, was validated independently by Battelle. When the effect of implementing a control technology was to increase, rather than decrease, the emission of a constituent, the resulting change is listed (in parenthesis).

Below each table is discussed how well a respective proponent's' NO_x and CO emissions data compared with those measured independently by BCO. This comparison was performed in two ways:
1) on an absolute basis: proponent emission-data-point vs. BCO emission-data-point, and
2) on a relative basis: proponent-observed-emission change vs. BCO-observed change.

TABLE 1. VALIDATION OF BKM DATA FOR DUAL-FUEL FIRING

TEST LAB	TEST FUEL	-86 LOAD (amps)	-86 STATUS	O_2 (am-%)	CO_2 (am-%)	NO_x (am-ppm)	CO (am-ppm)	RHC (am-ppm)	RO_x (spot no.)
BKM	DF2	Idle	Baseline	NM	NM	420	59	117	NM
BCO	DF2	Idle	Baseline	19.0	1.5	299	390	90	1
DIFFERENCE BETWEEN BKM & BCO DATA (%)				-	-	29	560	68	-
BKM	DF2	100	Baseline	NM	NM	1016	47	99	NM
BCO	DF2	100	Baseline	16.2	3.6	1151	50	120	1
DIFFERENCE BETWEEN BKM & BCO DATA (%)				-	-	13	6	71	-
BKM	DF2	200	Baseline	NM	NM	1744	134	84	NM
BCO	DF2	200	Baseline	12.9	6.0	2616	124	200	1
DIFFERENCE BETWEEN BKM & BCO DATA (%)				-	-	50	7	138	-
BKM	DF2	Idle	+ DFF	ND	ND	ND	ND	ND	ND
BCO	DF2	Idle	+ DFF	NM	NM	NM	NM	NM	NM
DIFFERENCE BETWEEN BKM & BCO DATA (%)				-	-	-	-	-	-
BKM	DF2	100	+ DFF	NM	NM	582	1066	11630	NM
BCO	DF2	100	+ DFF	16.2	3.6	937	1032	3700	1
DIFFERENCE BETWEEN BKM & BCO DATA (%)				-	-	61	3	68	-
BKM	DF2	200	+ DFF	NM	NM	1010	798	13339	NM
BCO	DF2	200	+ DFF	13.5	5.6	1503	809	4900	1
DIFFERENCE BETWEEN BKM & BCO DATA (%)				-	-	49	1	63	-
						REDUCTION (INCREASE) IN EMISSIONS (%)			
BKM	DF2	Idle	+ DFF			-	-	-	-
BCO	DF2	Idle	+ DFF			-	-	-	0
BKM	DF2	100	+ DFF			43	(2168)	(11650)	-
BCO	DF2	100	+ DFF			19	(1964)	(2983)	0
BKM	DF2	200	+ DFF			42	(495)	(15780)	-
BCO	DF2	200	+ DFF			43	(552)	(2350)	0

A/M32-86: Serial No. KZO0884 Date of Testing: 09/16/96 Site of Testing: San Diego, CA

For baseline tests, the average difference between BKM and BCO data was 31% for NO_x and 191% for CO. For DFF tests, the average difference was 55% for NO_x and 2% for CO. For all tests, the average difference between BKM and BCO data was 40% for NO_x and 115% for CO. Despite this variance, reductions in NO_x and increases in CO observed by BKM and BCO when DFF was implemented were comparable: 43% (NO_x), 500-2000% (CO), indirectly validating BKM data.

As will be shown, differences between proponent and BCO data were the greatest at BKM than at any other site. The reason for this apparent discrepancy remains unresolved, despite a second attempt to reproduce BKM data.

TABLE 2. VALIDATION OF WL/MNMW DATA FOR NON-THERMAL DISCHARGE

TEST LAB	TEST FUEL	-86 LOAD (amps)	-86 STATUS	O_2 (am-%)	CO_2 (am-%)	NO_x (am-ppm)	CO (am-ppm)	RHC (am-ppm)	RO_x (spot no.)
WL/MN	JP8	Idle	Baseline	NM	NM	235	300	NM	NM
BCO	JP8	Idle	Baseline	19.3	1.3	265	272	100	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	11	9	-	-
WL/MN	JP8	100	Baseline	NM	NM	637	60	NM	NM
BCO	JP8	100	Baseline	16.4	3.4	869	75	150	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	36	25	-	-
WL/MN	JP8	200	Baseline	ND	ND	ND	ND	ND	ND
BCO	JP8	200	Baseline	NM	NM	NM	NM	NM	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	-	-	-	-
WL/MN	JP8	Idle	+ NTD	NM	NM	20	275	NM	NM
BCO	JP8	Idle	+ NTD	20	0.8	20	259	90	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	0	6	-	-
WL/MN	JP8	100	+ NTD	NM	NM	197	220	NM	NM
BCO	JP8	100	+ NTD	16.6	3.3	205	202	165	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	4	8	-	-
WL/MN	JP8	200	+ NTD	ND	ND	ND	ND	ND	ND
BCO	JP8	200	+ NTD	NM	NM	NM	NM	NM	NM
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	-	-	-	-
						REDUCTION (INCREASE) IN EMISSIONS (%)			
WL/MN	JP8	Idle	+ NTD			92	8	-	-
BCO	JP8	Idle	+ NTD			92	5	10	0
WL/MN	JP8	100	+ NTD			69	(73)	-	-
BCO	JP8	100	+ NTD			76	(170)	(10)	0
WL/MN	JP8	200	+ NTD			-	-	-	-
BCO	JP8	200	+ NTD			-	-	-	-

A/M32A-86D: Serial No. 80PS01405 Date of Testing: 09/11/96 Site of Testing: Eglin AFB, Fort Walton Beach, FL

For baseline tests, the average difference between WL/MN and BCO data was 24% for NO_x and 17% for CO. For NTD tests, the average difference was 2% for NO_x and 7% for CO. For all tests, the average difference between WL/MN and BCO data was 13% for NO_x and 12% for CO. Most changes in NO_x and CO observed by WL/MN and BCO when NTD was implemented were comparable: ~92% reduction in NO_x and ~7% increase in CO. The increase in CO at 100 amps observed by BCO was somewhat higher than that observed by WL/MN. For the most part, therefore, WL/MN emissions data can be considered independently validated.

TABLE 3. VALIDATION OF AL/CFTS DATA FOR OXYGEN-ENRICHED AIR

TEST LAB	TEST FUEL	-86 LOAD (amps)	-86 STATUS	O_2 (am-%)	CO_2 (am-%)	NO_x (am-ppm)	CO (am-ppm)	RHC (am-ppm)	RO_x (spot no.)
AL/CFTS	DF2	Idle	Baseline	18.4	1.82	505	180	110	NM
BCO	DF2	Idle	Baseline	ND	ND	ND	ND	ND	ND
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
AL/CFTS	DF2	100	Baseline	ND	ND	ND	ND	ND	ND
BCO	DF2	100	Baseline	ND	ND	ND	ND	ND	ND
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
AL/CFTS	DF2	200	Baseline	ND	ND	ND	ND	ND	ND
BCO	DF2	200	Baseline	ND	ND	ND	ND	ND	ND
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
AL/CFTS	DF2	Idle	+ OEA	14.8	4.38	250	180	150	NM
BCO	DF2	Idle	+ OEA	ND	ND	ND	ND	ND	ND
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
AL/CFTS	DF2	100	+ OEA	ND	ND	ND	ND	ND	ND
BCO	DF2	100	+ OEA	ND	ND	ND	ND	ND	ND
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
AL/CFTS	DF2	200	+ OEA	ND	ND	ND	ND	ND	ND
BCO	DF2	200	+ OEA	ND	ND	ND	ND	ND	ND
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
						REDUCTION (INCREASE) IN EMISSIONS (%)			
AL/CFTS	DF2	Idle	+ OEA			50	0	(25)	-
BCO	DF2	Idle	+ OEA			-	-	-	-
AL/CFTS	DF2	100	+ OEA			-	-	-	-
BCO	DF2	100	+ OEA			-	-	-	-
AL/CFTS	DF2	200	+ OEA			-	-	-	-
BCO	DF2	200	+ OEA			-	-	-	-

A/M32A-86D: Serial No. KZO2108 Date of "Testing": 09/20/96 Site of "Testing": Brooks AFB, San Antonio, TX

On-site validation tests could not be performed on the OEA emissions-control technology because of apparent scheduling problems. As a substitute procedure, BCO traveled to AL/CFTS and calibrated its ENERAC against: 1) an NIST-traceable standard for NO, and 2) the emissions from a diesel engine, which were being co-monitored by a AL/CFTS chemiluminescent analyzer.

BCO reproduced the NIST NO-calibration gas concentration to within $\sim 1\%$ (947 vs. 936 ppm NO), and reproduced emissions from the diesel engine to within $\leq 2\%$ (660 vs. 644 ppm NO; 794 vs. 784 ppm NO_x). Hence, the above data for the OEA technology can be considered independently validated, albeit indirectly so.

TABLE 4. VALIDATION OF HIS DATA FOR SELECTIVE-CATALYTIC REDUCTION

TEST LAB	TEST FUEL	-86 LOAD (amps)	-86 STATUS	O_2 (am-%)	CO_2 (am-%)	NO_x (am-ppm)	CO (am-ppm)	RHC (am-ppm)	RO_x (spot no.)
HIS	DF2	Idle	Baseline	19.0	1.5	175	525	NM	NM
BCO	DF2	Idle	Baseline	19.3	1.3	164	494	100	1
DIFFERENCE BETWEEN HIS & BCO DATA (%)				2	13	5	6	-	-
HIS	DF2	100	Baseline	15.0	4.0	690	68	NM	NM
BCO	DF2	100	Baseline	16.0	3.7	656	60	130	1
DIFFERENCE BETWEEN HIS & BCO DATA (%)				7	8	5	12	-	-
HIS	DF2	200	Baseline	12.5	6.5	1250	160	NM	NM
BCO	DF2	200	Baseline	12.3	6.5	1310	178	190	1
DIFFERENCE BETWEEN HIS & BCO DATA (%)				4	0	5	11	-	-
HIS	DF2	Idle	+ SCR	19.5	1.0	135	375	NM	NM
BCO	DF2	Idle	+ SCR	19.5	1.1	128	354	50	1
DIFFERENCE BETWEEN HIS & BCO DATA (%)				0	10	5	6	-	-
HIS	DF2	100	+ SCR	16.5	4.0	450	60	NM	NM
BCO	DF2	100	+ SCR	16.1	3.6	486	56	75	1
DIFFERENCE BETWEEN HIS & BCO DATA (%)				2	10	7	6	-	-
HIS	DF2	200	+ SCR	12.0	7.0	50	10	NM	NM
BCO	DF2	200	+ SCR	12.2	6.6	52	9	80	1
DIFFERENCE BETWEEN HIS & BCO DATA (%)				2	6	4	10	-	-
						REDUCTION (INCREASE) IN EMISSIONS (%)			
HIS	DF2	Idle	+ SCR			23	29	-	-
BCO	DF2	Idle	+ SCR			21	28	50	0
HIS	DF2	100	+ SCR			35	12	-	-
BCO	DF2	100	+ SCR			26	7	42	0
HIS	DF2	200	+ SCR			96	93	-	-
BCO	DF2	200	+ SCR			96	96	56	0

A/M32A-86: Serial No. KZ0913 Date of Testing: 09/19/96 Site of Testing: Houston, TX

For baseline tests, the average difference between HIS and BCO data was 5% for NO_x and 10% for CO. For SCR tests, the average difference was 5% for NO_x and 7% for CO. For all tests, the difference between HIS and BCO data was 5% for NO_x and 9% for CO. Most reductions in NO_x and in CO observed by HIS and BCO, when SCR technology was implemented, were comparable: 22%, 30%, and 96% in NO_x, and 28%, 10%, and 95% in CO at 0, 100 and 200 amps, respectively. As such, HIS emissions data can be considered independently validated.

TABLE 5. VALIDATION OF WL/FIVC DATA FOR WATER-IN-FUEL FIRING

TEST LAB	TEST FUEL	-86 LOAD (amps)	-86 STATUS	O_2 (am-%)	CO_2 (am-%)	NO_x (am-ppm)	CO (am-ppm)	RHC (am-ppm)	RO_x (spot no.)
WL/FIVC	DF2	Idle	Baseline	NM	NM	200	300	NM	NM
BCO	DF2	Idle	Baseline	19.7	1.0	220	350	NM	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	10	16	-	-
WL/FIVC	DF2	100	Baseline	NM	NM	1450	60	NM	NM
BCO	DF2	100	Baseline	15.9	4.1	1485	55	NM	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	2	8	-	-
WL/FIVC	DF2	200	Baseline	NM	NM	2520	125	NM	NM
BCO	DF2	200	Baseline	12.4	6.8	2640	50	NM	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	5	8	-	-
WL/FIVC	DF2	Idle	+ WFF	NM	NM	10	1500	NM	NM
BCO	DF2	Idle	+ WFF	19.4	1.3	8	1480	NM	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	20	2	-	-
WL/FIVC	DF2	100	+ WFF	NM	NM	140	1500	NM	NM
BCO	DF2	100	+ WFF	15.5	4.3	110	1770	NM	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	20	18	-	-
WL/FIVC	DF2	200	+ WFF	NM	NM	380	60	NM	NM
BCO	DF2	200	+ WFF	12.4	6.8	390	50	NM	1
DIFFERENCE BETWEEN WL & BCO DATA (%)				-	-	3	17	-	-
						REDUCTION (INCREASE) IN EMISSIONS (%)			
WL/FIVC	DF2	Idle	+ WFF			95	(400)	-	-
BCO	DF2	Idle	+ WFF			96	(375)	-	0
WL/FIVC	DF2	100	+ WFF			90	(2400)	-	-
BCO	DF2	100	+ WFF			93	(3100)	-	0
WL/FIVC	DF2	200	+ WFF			84	52	-	-
BCO	DF2	200	+ WFF			85	63	-	0

A/M32A-86D: Serial No. KZ03464 Date of Testing: 08/19/96 Site of Testing: Tyndall AFB, Panama City, FL

For baseline tests, the average difference between WL/FIVC and BCO data was 6% for NO_x and 11% for CO. For WFF tests, the average difference was 14% for NO_x and 12% for CO. For all tests, the difference between WL/FIVC and BCO data was 10% for NO_x and 12% for CO. Most changes in NO_x and CO observed by WL and BCO when WFF was implemented were comparable: 95%, 92%, 85% reductions in NO_x; 385%, 1500% increase, 58% decrease in CO at 0, 100, and 200 amps, respectively. As such, WL/FIVC emissions data can be considered independently validated.

TABLE 6. VALIDATION OF AL/EQ DATA FOR NOx-FILTER CART

TEST LAB	TEST FUEL	-86 LOAD (amps)	-86 STATUS	O_2 (am-%)	CO_2 (am-%)	NOx (am-ppm)	CO (am-ppm)	RHC (am-ppm)	RO_x (spot no.)
AL/EQ	DF2	Idle	Baseline	NM	NM	250	75	NM	NM
BCO	DF2	Idle	Baseline	19.8	0.7	235	90	100	1
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	6	20	-	-
AL/EQ	DF2	100	Baseline	NM	NM	1120	20	NM	NM
BCO	DF2	100	Baseline	16.3	2.7	965	20	150	1
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	14	0	-	-
AL/EQ	DF2	200	Baseline	ND	ND	ND	ND	ND	ND
BCO	DF2	200	Baseline	NM	NM	NM	NM	NM	NM
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
AL/EQ	DF2	Idle	+ NFC	NM	NM	0	0	NM	NM
BCO	DF2	Idle	+ NFC	20.6	0.2	0	0	0	1
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	0	0	-	-
AL/EQ	DF2	100	+ NFC	NM	NM	50	0	NM	NM
BCO	DF2	100	+ NFC	16.5	2.6	50	0	0	1
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	0	0	-	-
AL/EQ	DF2	200	+ NFC	ND	ND	ND	ND	ND	ND
BCO	DF2	200	+ NFC	NM	NM	NM	NM	NM	NM
DIFFERENCE BETWEEN AL & BCO DATA (%)				-	-	-	-	-	-
						REDUCTION (INCREASE) IN EMISSIONS (%)			
	DF2	Idle	+ NFC			100	100	-	-
BCO	DF2	Idle	+ NFC			100	100	100	0
	DF2	100	+ NFC			96	100	-	-
BCO	DF2	100	+ NFC			92	100	100	0
	DF2	200	+ NFC			-	-	-	-
BCO	DF2	200	+ NFC			-	-	-	-

A/M32-86: Serial No. ?

Date of Testing: 08/28/96

Site of Testing: McClellan AFB, Sacramento, CA

For baseline tests, the average difference between AL/EQ and BCO data was 10% for NO_x and 10% for CO. For NFC tests, the average difference was 0% for NO_x and 0% for CO. For all tests, the difference between AL/EQ and BCO data was 5% for NO_x and 5% for CO. ALL NO_x and CO reductions observed by AL/EQ and BCO when NFC technology was implemented were comparable: 100% and 94% in NO_x, and 100% and 100% in CO, at 0 and 100 amps, respectively. As such, AL/EQ emissions data can be considered independently validated.

Overall, emissions data collected by Green AGE-technology proponents were reproduced, to a large extent, either directly or indirectly, by independent measurements by BCO.

Two additional analyses were conducted to confirm this validation, as follows. First, differences between the two data bases were arithmetically averaged, yielding 15 $\pm$ 17% for NO_x, and 31 $\pm$ 108% for CO. An international program has recently determined that the extent to which NO_x and CO emissions can be reproduced by different laboratories, under conditions conducive to reproducibility, is $\pm$ 9% for NO_x and $\pm$ 48% for CO [7]. Hence, CO data of BCO adequately reproduce Green AGE-technology proponent data, whereas NO_x data do so to a lesser extent.

The analysis continued by qualifying the absolute standard deviations in the average differences in NO_x and CO. When the absolute standard deviation exceeds an arithmetic average, as it does for the NO_x and CO averages, the data are not represented by bell-shaped curves, but are "skewed". In other words, a small number of high or low values is obscuring the significance of a larger number of high or low averages [8]. These artificially biasing data are "outliers". Hence, an alternative approach to averaging is needed. Under these conditions, geometric averaging is more statistically valid than arithmetic averaging [8]. Geometric averages for the differences between the NO_x and CO data bases are 10% and 10%, respectively (not 15% and 31%). This more appropriate averaging reveals that the reproducibility between the NO_x and CO data bases is as good as can be expected, again confirming the validity of emission data of Green AGE-technology proponents and of BCO. The apparent "outlying" data were those collected at BKM.

The second analysis compared BCO -86 baseline data with those of Pacific Environmental Services (PES) [6]. In the PES study, NO_x and CO emissions from four -86s were measured in triplicate at 100 and 200 amps. A comparison of PES and BCO emissions data is given in Table 7. As shown, BCO NO_x and CO data are within the uncertainty of those measured by PES, again confirming the validity of BCO data, as well as those of the Green AGE- technology proponents.

TABLE 7. VALIDATION OF BCO BASELINE DATA FOR -86s

TEST LAB	TEST FUEL	-86 LOAD (amps)	-86 STATUS	O_2 (am-%)	NO_x (am-ppm)	CO (am-ppm)
PES	DF2	100	Baseline	16.5 $\pm$ 0.3	1171 $\pm$ 181	47 $\pm$ 7
BCO	DF2	100	Baseline	16.2 $\pm$ 0.2	1025 $\pm$ 280	51 $\pm$ 18
PES	DF2	200	Baseline	13.0 $\pm$ 0.5	2118 $\pm$ 260	94 $\pm$ 30
BCO	DF2	200	Baseline	12.5 $\pm$ 0.3	2189 $\pm$ 321	145 $\pm$ 23

7.0 SUMMARY

Reported are results of a US Air Force effort to reduce air emissions from aerospace ground equipment (AGE), referred to as the "Green AGE" Initiative.

In Phase I, promising NO_x-reduction technologies were identified. In Phase II, these technologies were demonstrated on an A/M32A-86 ("-86") generator, and evaluated by Battelle as "Honest Broker". On-site measurements were made to verify that data gathered by technology proponents were valid, and could be used in the competitive evaluation of technologies in Green AGE Phase III, which is also being performed by Battelle. Emissions measurements were performed in triplicate using EPA-recommended procedures, with the -86 operating at 0, 100, and 200 amps.

The 6 candidate emissions-reduction technologies, their proponents, and locations, were:

- Dual-Fuel Firing (DFF), BKM, San Diego, CA;
- Non-Thermal Discharge (NTD), WL/MNMW, Eglin AFB, FL;
- Oxygen Enriched Air (OEA), AL/CFTS, Brooks AFB, TX;
- Selective-Catalytic Reduction (SCR), Houston Industrial Silencing (HIS), Houston, TX;
- Water-in-Fuel Firing (WFF), WL/FIVC, Tyndall AFB, FL; and
- NO_x-Filter Cart (NFC), AL/EQ, Tyndall AFB, CA.

Emissions data were reproduced by independent Battelle measurements and analyses. Confirmed NO_x reductions, which will be used for the Green AGE Phase III evaluation, were:

- ~43% for DFF,
- ~70-92% for NTD,
- ~50% for OEA,
- ~22-96% for SCR,
- ~85-95% for WFF, and
- ~92-100% for NFC.

8.0 REFERENCES

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